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HYBRID HYDROSTATIC/BALL BEARINGS IN HIGH-SPEED TURBOMACHINERY

January 1983

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prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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N. Hannum, Project Manager

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16. Abstract
A high-speed, high-pressure liquid hydrogen turbopump was designed, fabricated, and tested under a previous contract. This design was then modified to incorporate hybrid hydrostatic/ball bearings on both the pump end and turbine end to replace the original conventional ball bearing packages. The design, analysis, turbopump modification, assembly, and testing of the turbopump with hybrid bearings is presented here. Initial design considerations and rotordynamic performance analysis was made to define expected turbopump operating characteristics and are reported. The results of testing the turbopump to speeds of 9215 rad/s (88,000 rpm) using a wide range of hydrostatic bearing supply pressures are presented. The hydrostatic bearing test data and the rotordynamic behavior of the turbopump was closely analyzed and are included in the report. The testing of hybrid hydrostatic/ball bearings on a turbopump to the high-speed requirements has indicated the configuration concept is feasible. The program has presented a great deal of information on the technology requirements of integrating the hybrid bearing into high-speed turbopump designs for improved bearing life.

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FOREWORD

The work presented herein was conducted from 29 August 1980 to 15 December 1982 by personnel from the Engineering and Test Units at Rocketdyne, a division of Rockwell International, under Contract NAS 3-22480. Mr. Ned Hannum, Lewis-Research Center, was the NASA Project Manager. At Rocketdyne, Messrs. Harold Diem, Program Manager, and Charles Nielson, Project Engineer, were responsible for the direction of the program.

Important contributions to the conduct of the program and to the preparation of the report material were made by the following Rocketdyne personnel:

Turbomachinery	Dr. Wei-Chung-Chen Mr. J. L. Boynton
Mechanical Elements	Mr. Myles Butner Mr. Francis Lee
Structural Dynamics	Mr. R. Beatty Mr. M. Wagner Mr. B. Rowan
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Chemical and Advanced Component Test	Mr. J. C. Pulte Mr. G. A. Hood
Turbomachinery Design	Mr. H. Buddenbohm Mr. J. Galazin

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SUMMARY

The objective of this program was to retrofit a Mark 48 fuel turbopump with hybrid hydrostatic/ball bearings and to demonstrate hybrid bearing feasibility and performance through turbopump testing. Requirements for future space maneuvering missions have indicated the need for the improvement in operational life of small high-speed liquid hydrogen turbopumps. The mission requirements dictate long life operation at high speeds and with many starts. Of major concern is the long-life reliability of conventional ball bearings when subjected to these operating conditions. The hybrid bearing was developed with the intent of having the capacity to operate as a conventional bearing and carry axial thrust and radial loads of the shaft during turbopump transient startup and shutdown while being able to utilize the hydrostatic bearing at high speeds with the ball bearing outer and inner races rotating with the shaft. This solid body rotation, while operating as a hydrostatic bearing at high speed, would reduce ball bearing wear and extend overall bearing life. The specific objectives of this program were to design, analyze, and fabricate hybrid bearings and modify the Mark 48-F turbopump for operation with them. The additional objective was to test the turbopump with the bearings using both external and internal (pump supplied) hydrostatic bearing supply fluid.

At the beginning of the program, an analytical study was made to determine the predicted operating characteristics of the hybrid bearings and the critical design dimensions of hydrostatic bearing clearance and orifice size. Also required were decisions as to where the hydrostatic bearing fluid supply would be taken from the pump in the internally supplied mode. Hydrostatic bearing performance predictions were made for direct and cross-coupled stiffness and damping characteristics as a function of turbopump speed and supply pressures. The analytical predictions available were used for turbopump rotordynamic analysis to determine critical speed, stability, and response of the rotor within the turbopump housing. The spring rate of the turbopump housing coupled to the rotor was included in the analysis. This was done using the advanced superposition methods developed for high-speed turbopump vibration analysis developed early in the program as a part of this contract effort. The objectives and results of that study have been reported in CR-15970, "Interim Report - Advanced Superposition Methods for High-Speed Turbopump Vibration Analysis," May 1981.

The rotordynamic analysis of the turbopump provided interesting operational predictions. The hydrostatic bearing pressure and flow supplied by the turbopump increases as pump speed increases, which causes the hydrostatic bearing stiffness to increase with an attendant increase in critical speed. This results in the natural frequency of the rotor tracking the rotor speed. Changes in hydrostatic bearing parameters (clearances, orifice size, and supply pressure levels) were found analytically to shift the natural frequency of the rotor. It was found that supply pressure levels held constant with speed change at or below the pressures consistent with the pump-supplied pressure caused the rotor natural frequency to

be constant. The results did indicate that with a wide range of supply pressures and some design latitude the critical speed and stability of the rotor can be controlled on the turbopump.

The design of the hybrid bearings and the turbopump modification was completed. The turbopump was carefully assembled with emphasis given to dynamic balancing of the rotor. Procedures for rotor assembly and balancing were developed to minimize the imbalance changes during rotor housing assembly. The assembled turbopump was installed in the Advanced Propulsion Test Facility at the Rocketdyne Santa Susana Field Laboratory. A large amount of instrumentation was incorporated on the facility and turbopump to record dynamic and steady-state operating characteristics including shaft radial and axial motion. A pressure control system was developed and installed to simulate pump-fed (internal) flow supply pressure to the hydrostatic bearings or other selected pressure profiles as a function of shaft speed. The supply temperature, pressure, and flowrate were measured for all test conditions. The turbopump was operated in 15 tests for a total test time of 1,261 seconds of shaft speed rotation. Maximum shaft speeds in excess of 9,110 rad/s (87,000 rpm) were achieved. During the tests, the pump-end hydrostatic bearing cartridge speed followed and matched shaft speeds up to approximately 7,330 rad/s (70,000 rpm). Above that speed, the pump-end cartridge speed lagged shaft speed. This always occurred with a condition of high casing vibration levels and shaft orbiting amplitudes. The turbine-end bearing did not generally rotate with the shaft speed due to end-play restrictions imposed on it by the basic turbopump design. The tests were run using externally supplied liquid hydrogen to the bearings during one test series and pump-fed liquid hydrogen to the bearings on another test series. High vibration levels were observed at high-speed operation and subsynchronous instability occurred on two high-speed tests at the end of the test series.

The test data were reduced and reviewed in detail. The results were coupled with the results of the turbopump disassembly and component inspection. The conclusions from the test results are that the turbopump has proven it can operate with hybrid hydrostatic/ball bearings at high-speed levels. The test and analysis experience points out the need for the ability to accurately predict the dynamic coefficients of the hydrostatic bearing to accurately determine the hybrid bearing operating conditions required. This will allow the hybrid bearing to operate where, with proper controls, the rotordynamic conditions are favorable to the turbopump for quiet, smooth operation. The problems inherent with design of hybrid bearings for turbopump operation have been closely explored during this study, and solutions to many of these problems were determined. It is recommended that further study be made in specific areas of hydrostatic bearing technology so implementation of the hybrid bearings into turbopump designs can be accomplished.

INTRODUCTION

Vehicle requirements for future space maneuvering missions indicate the need for development of small, high-pressure liquid hydrogen turbopumps These missions require high-speed operation for a long life, with many starts in a unit of minimum weight and envelope. A small, high pressure hydrogen turbopump has been designed, fabricated, and tested by Rocketdyne under NASA-LeRC direction. The objective of this program was to retrofit a Mark 48-F turbopump with the objective of extending the state of the art by demonstrating, through testing, the ability of the turbopump to operate with hybrid hydrostatic/ball bearings.

Prior effort by Rocketdyne on the small, high-pressure hydrogen turbopump, under the direction of NASA-Lewis Research Center (LeRC), was accomplished under Contracts NAS 3-17794 and NAS 3-21008 (Ref. 1). Past efforts included fluid dynamic and mechanical analysis and design to produce a liquid hydrogen turbopump for a 20,000-pound-thrust staged-combustion cycle engine for orbital transfer vehicle applications. The turbopump design developed is the Mark 48 fuel turbopump which contains three centrifugal shrouded impeller stages preceded by an axial inducer (Fig. 1). The impeller stages are followed by internal crossover passages and a diffuser and volute on the final stage. The turbopump is driven by a two-stage axial flow reaction turbine driven by hot combustion products of hydrogen and oxygen. The design speed is 9,948 rad/s (95,000 rpm).

Three test series had previously been performed on the turbopump with several design modifications developed between test series. These include design changes from a scroll-type inlet to an axial inlet with added inducer stage and opening up the first-stage impeller eye for improved suction performance. Tests speeds to 9,739 rad/s (93,000 rpm) and pump discharge pressures to 2885 N/cm^2 (4,182 [illegible]) have been achieved, using gaseous hydrogen as the turbine drive fluid. Exce[illegible] suction performance has been shown with measured head rise and isentropic ef[illegible]ncy higher than predicted. On the last test series, a resonant condition was found at approximately 9,634 rad/s (92,000 rpm), causing unacceptable vibration levels limiting further testing at design speed.

The program plan of this study was defined in two basic phases. The first phase consisted of one technical task and a reporting task. The vibration analysis task consisted of preliminary "ringing" or rap testing of the turbopump rotor and the assembled housing without the rotor to determine the resonance characteristics (frequencies and mode shapes) of each assembly. A modal analysis was used to determine the cause of the resonance condition. An interim report summarizing the results was published following the vibration analysis program (Ref. 3).

The second phase of the contract, which is reported herein, consisted of design, analysis, and modification of the turbopump to incorporate hybrid hydrostatic/ball bearings in both the pump and turbine-end bearing packages. The completed turbopump configuration was assembled and tested and the data analyzed to demonstrate the capability of the bearings to operate effectively within a turbopump.

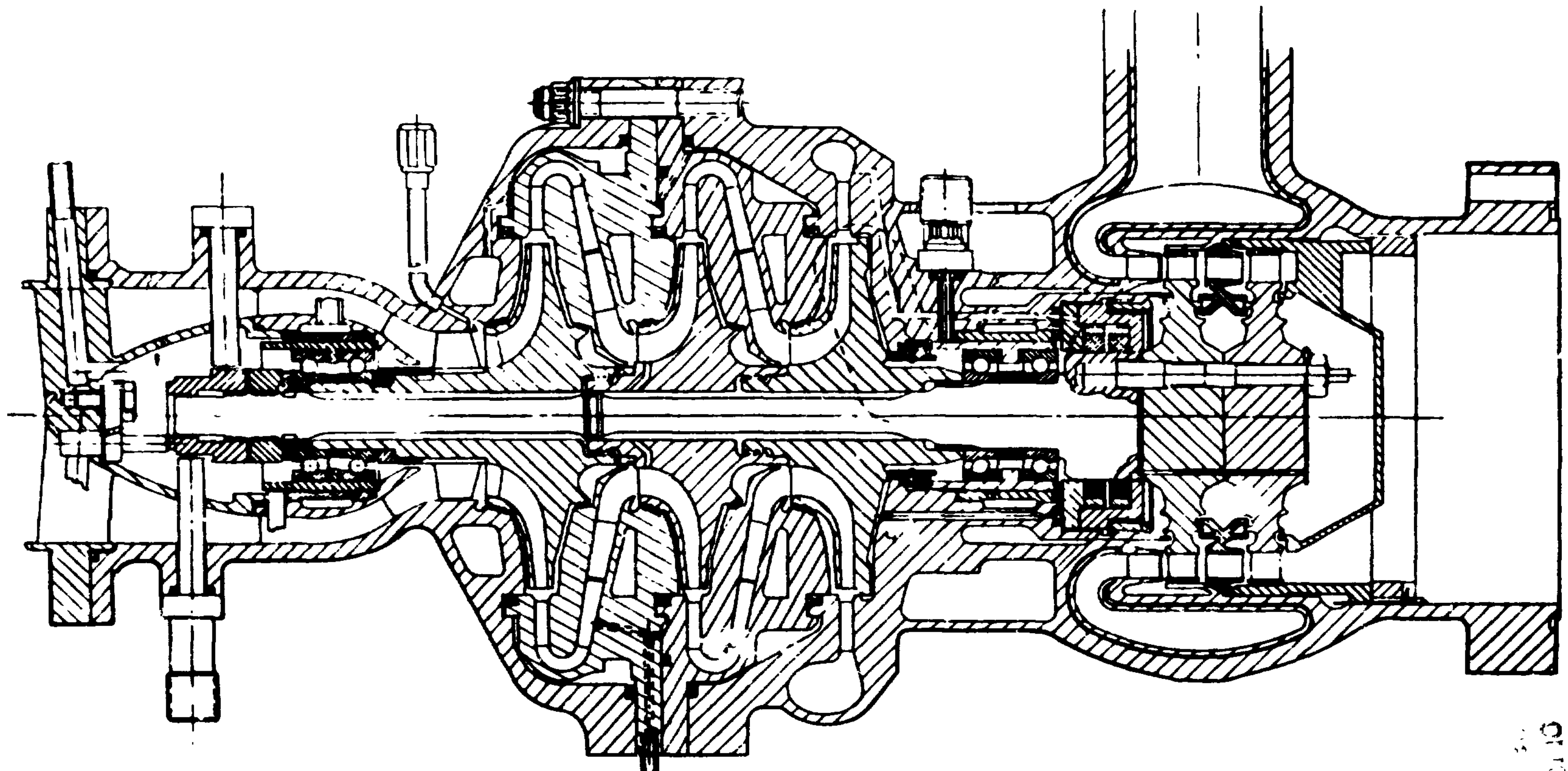

Figure 1. Hybrid Hydostatic/Ball Bearings in Mark 48-F Turbopump

As early as 1969, a hybrid bearing was tested by Rocketdyne to a speed of 2,870 rad/s (27,400 rpm) in Freon 12. The major analytical and test activity occurring in the study of hybrid hydrostatic/ball bearings has been that of the NASA-Lewis Research Center. Through the 1970's to the present, hybrid bearing designs were tested at NASA-LeRC and the basic configurations developed there and at MTI (Ref. 2) were helpful in selecting the bearing design for these turbopump tests. A major achievement made during the period of study was the development of analytical models to predict hydrostatic bearing behavior and stiffness and damping coefficients. At present, only the data from the tests of NASA-LeRC are available to correlate with the analytically predicted direct stiffness. Programs to directly measure the direct stiffness and damping are in progress in a test and analysis program at Rocketdyne sponsored by NASA-LeRC, Contract NAS 3-23263, and entitled "SSME Long-Life Bearing Program." During the program reported herein, it has been evident that accurate prediction of the hybrid bearing dynamic coefficients are required to utilize hybrid bearings in high-speed turbomachinery and control the critical speeds and rotordynamic stability. A significant beneficial product of the hydrostatic bearing is that there is some degree of stiffness and damping control simply by changing supply pressure to the bearing. This can be done easily during operation without requirements of access to the bearings or rotor for mechanical adjustments.

The benefits of using hybrid bearings within a high-speed turbopump are readily recognizable in extended bearing life and start capability. Present high-speed turbopump designs are prevented from achieving minimum size and weight and maximum efficiency by shaft speed limitations. With the development of the hybrid bearing, the ceiling on shaft speed and bearing DN values for reliable operation will be removed and the turbopumps capability and efficiency per unit weight will be enhanced greatly. The purpose of this study was to determine the feasibility of operating with the hybrid bearings in a high-speed turbopump. The results of the study indicate that although some technology is limited, it can be developed and the hybrid bearing design concept has great merit in meeting the objectives of higher speed, smaller, more efficient, and reliable turbomachinery.

DISCUSSION

HYBRID BEARING DESIGN

The design of the hydrostatic bearing packages was incorporated into the Mark 48 fuel turbopump (Fig. 1 and Appendix A). This was coordinated by a design study that determined the configuration requirements of the hydrostatic bearings and how to incorporate them into the existing turbopump envelope. A hybrid hydrostatic/ball bearing design had previously been developed for testing by NASA-LeRC and MTI (Ref. 2). A review of the basic design of these bearings was made and it was determined that the basic configuration of the bearings should be utilized in the turbopump. This would provide a solid data base for correlation between the MTI hydrostatic bearing performance predictions, NASA-LeRC test data, and the independent Rocketdyne performance analysis. The turbopump tests would provide dynamic performance data that could be correlated back to dynamic performance predictions based on the combined data base. After a review of the available data, the basic ground rules for the hydrostatic bearing design were agreed upon by Rocketdyne and NASA-LeRC Project Management.

The ground rules agreed upon for the conversion of the existing Mark 48 fuel turbopump with conventional ball bearings to the hybrid hydrostatic/ball bearing configuration was as follows:

- Maintain basic MTI design of details
    - NASA-LeRC test configuration data available
    - Duplicate basic pad and orifice configuration
- Utilize materials agreed upon
    - Journals and bearings - Inconel 718; thin dense chrome-plated journals
    - Silver plating on bearing inside diameter (bearing surface)
    - Axial stops on turbine bearing - Bearium B-10
    - Armalon cages on ball bearings
- Design must allow conversion back to ball bearing configuration
- Use special care in rotating assembly balancing
- Instrumentation requirements were defined for
    - Pressure
    - Temperature
    - Axial and radial position
    - Shaft and journal rotating speed

The basic design details of the hybrid hydrostatic/ball bearing was to generally match that of the NASA-LeRC test bearing configuration. The pad and orifice

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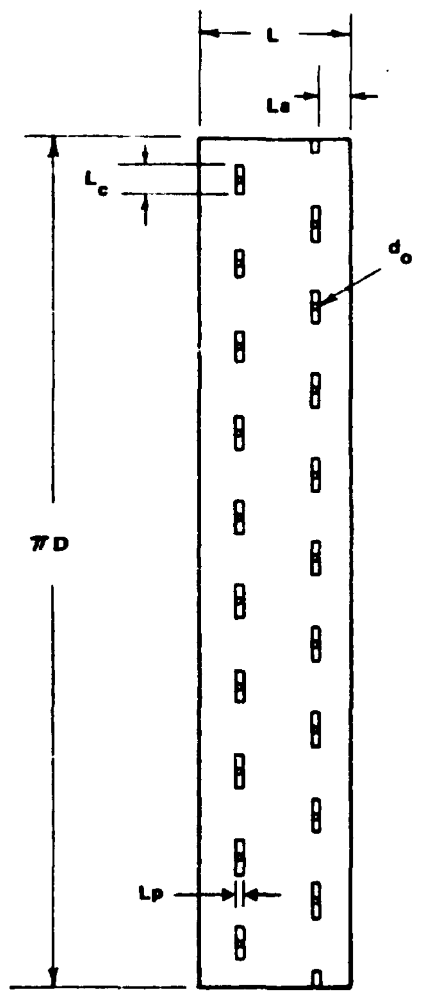
configuration and number would duplicate that previously tested. This pad configuration is given in Fig. 2. The bearings and journals were made of Inconel 718 to match the material of the turbopump housings. The rotating journals were to be ground and then plated with thin, dense chrome and the static bearing surfaces were to be plated with silver from 0.025 mm (0.001 inch) to 0.102 mm (0.004 inch) thick. The axial stops on the turbine bearing for transient axial thrust control were fabricated of a lead impregnated bronze alloy designated as Bearium B-10. The modifications to the turbopump were also to be made to allow conversion back to the conventional ball bearing configuration if required.

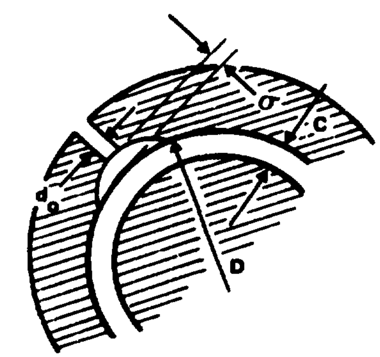
The selection of the orifice size and the hydrostatic bearing clearance was determined by hydrostatic analysis and the effects of these two parameters on bearing stiffness and damping. These parameters were used to extend the analysis to determine critical speed and dynamic response and stability of the rotor system. A wide range of operating diametral clearances from 0.0152 mm (0.0006 inch) to 0.061 mm (0.0024 inch) were considered in the selection process. The orifice size was dictated by the requirement to have the pressure ratio (fluid film pressure drop to the overall pressure drop) value of between 0.3 and 0.6 through the range of operating speeds and conditions. This analysis will be discussed fully in a later section of this report.

The basic features of the pump-end bearing package modifications for the Mark 48 fuel turbopump are shown in Fig. 3 and 4 in two separate views. The pump-end bearing flow supply enters two radial supply tubes (Fig. 3) to feed the circular hydrostatic bearing manifold over the bearings. The flow then enters through 2 rows of 10 orifices each, equally spaced around the bearing, and drops into the bearing pad. It is then distributed into the fluid film of the bearing-to-cartridge interface and flows axially outward to discharge into the cavity on either side of the bearing. The discharged flow is drained overboard in the bearing flow discharge lines (Fig. 3). The shaft speed is measured by a magnetic speed sensor (Fig. 3). The radial position of the shaft is recorded by two radial position transducers angularly spaced 90 degrees apart (Fig. 4). Journal rotative speed and radial position was recorded by one of two probe ports situated over the journal which is overhung past the ball bearings for that purpose (Fig. 4). One of these two ports was dedicated early in the program to accommodate the use of three small pressure transfer lines which measured bearing pad pressures in the hydrostatic bearing. A shaft axial position probe was also located in the pump inlet centerbody, as was a pressure measurement for sump pressure, both exiting from the inlet flange as shown in Fig. 4.

The turbine hybrid bearing design features are summarized in Fig. 5. Two bearing supply lines supply fluid to the supply manifold. Both pump and turbine-end bearings are generally of similar design. The two major differences of the bearings are the discharge flow of the turbine-end bearing shares the cavity with the balance piston flow from the aft side of the third-stage impeller. This flow is returned to the second-stage impeller inlet through the space between the center of the impeller hubs and the drawbolt (Appendix A). The resistance of this flow path was decreased to handle the added flow from the hydrostatic bearing. The pump-end hydrostatic bearing fluid is drained overboard. Two ports were added to the turbine-end bearing area. One was used for a radial position transducer



DEVELOPED BEARING SURFACE



AXIAL VIEW SHOWING TYPICAL POCKET PROFILE

FINAL BEARING DIMENSIONS

	TURBINE-END BEARING		PUMP-END BEARING	
	CENTIMETERS	INCH	CENTIMETERS	INCH
D	= 4.4392	1.74	4.4313	1.7446
C AT	= 0.00305	9500 RPM = 0.0012	0.00305	0.0012
[illegible]	= 0.0610	0.024	0.0610	0.024
σ	= 0.0610	0.024	0.0610	0.024
L	= 2.438	0.925	2.413	0.950
Lc	= 0.508	0.2	0.508	0.200
La	= 0.508	0.2	0.508	0.200
Lp	= 241	0.095	0.241	0.095

Figure 2. Hybrid Hydrostatic/Ball Bearing Design Dimensions

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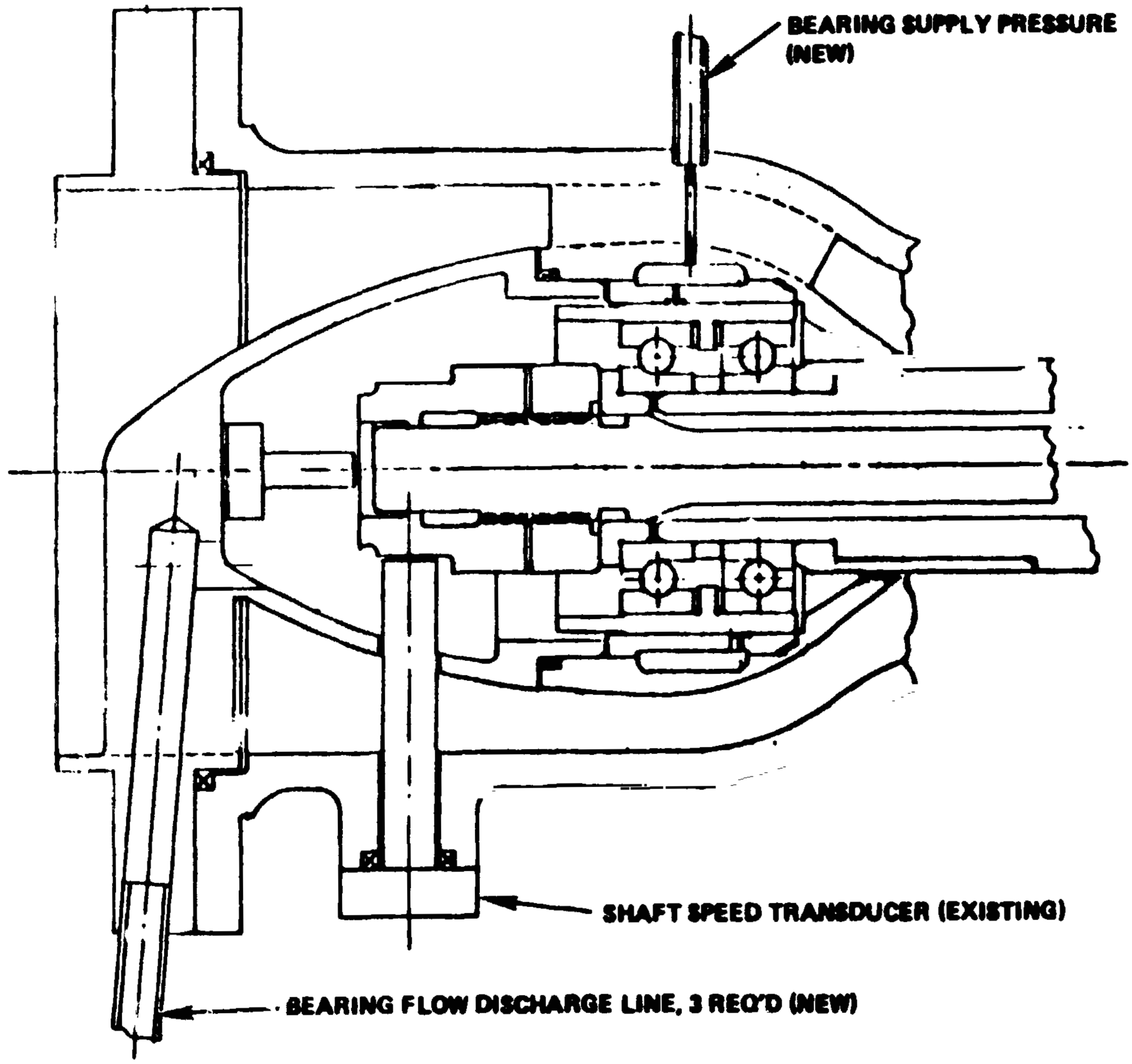

Figure 3. Pump Bearing Design Features (View 1)

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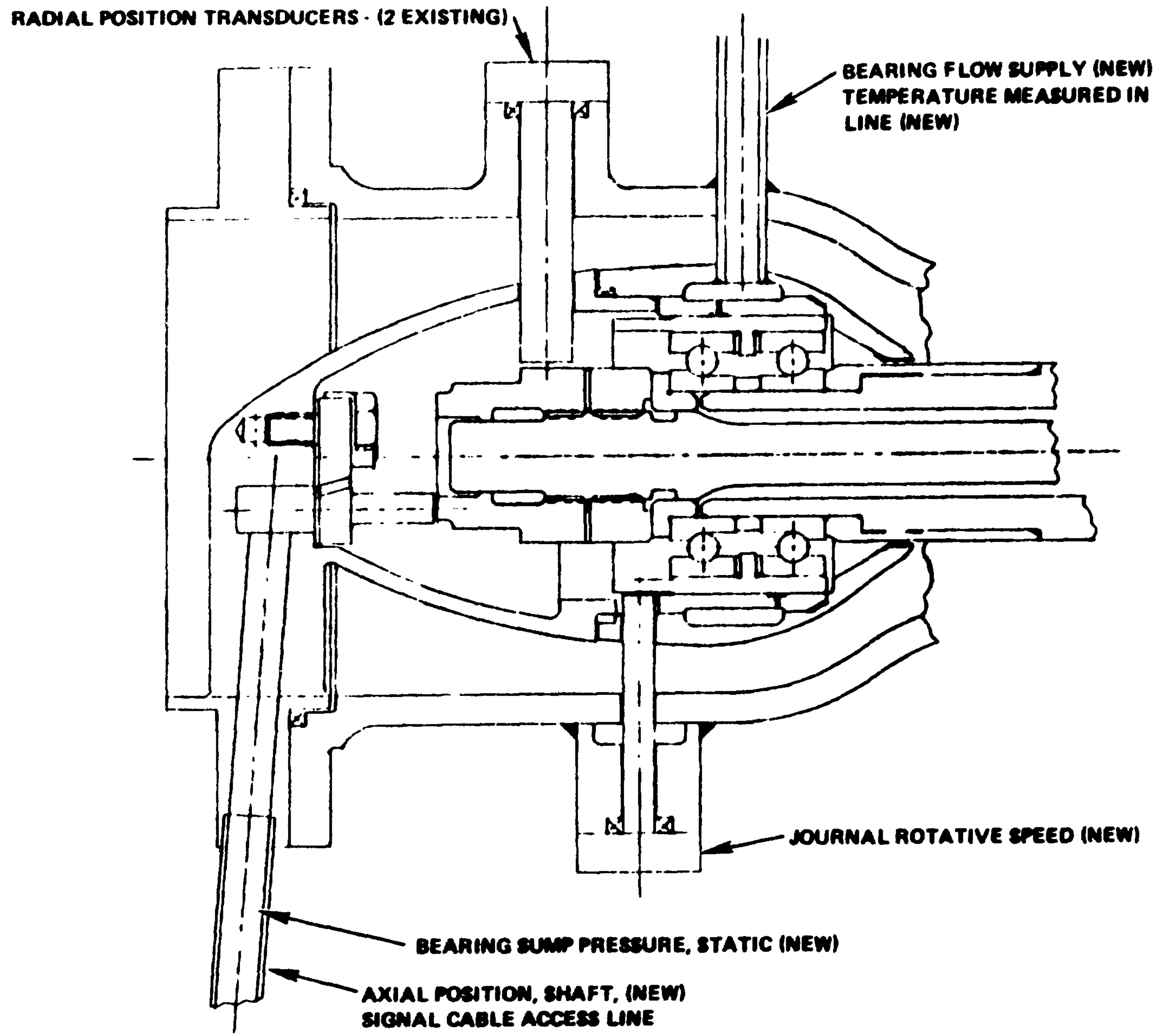

Figure 4. Pump Bearing Design Features

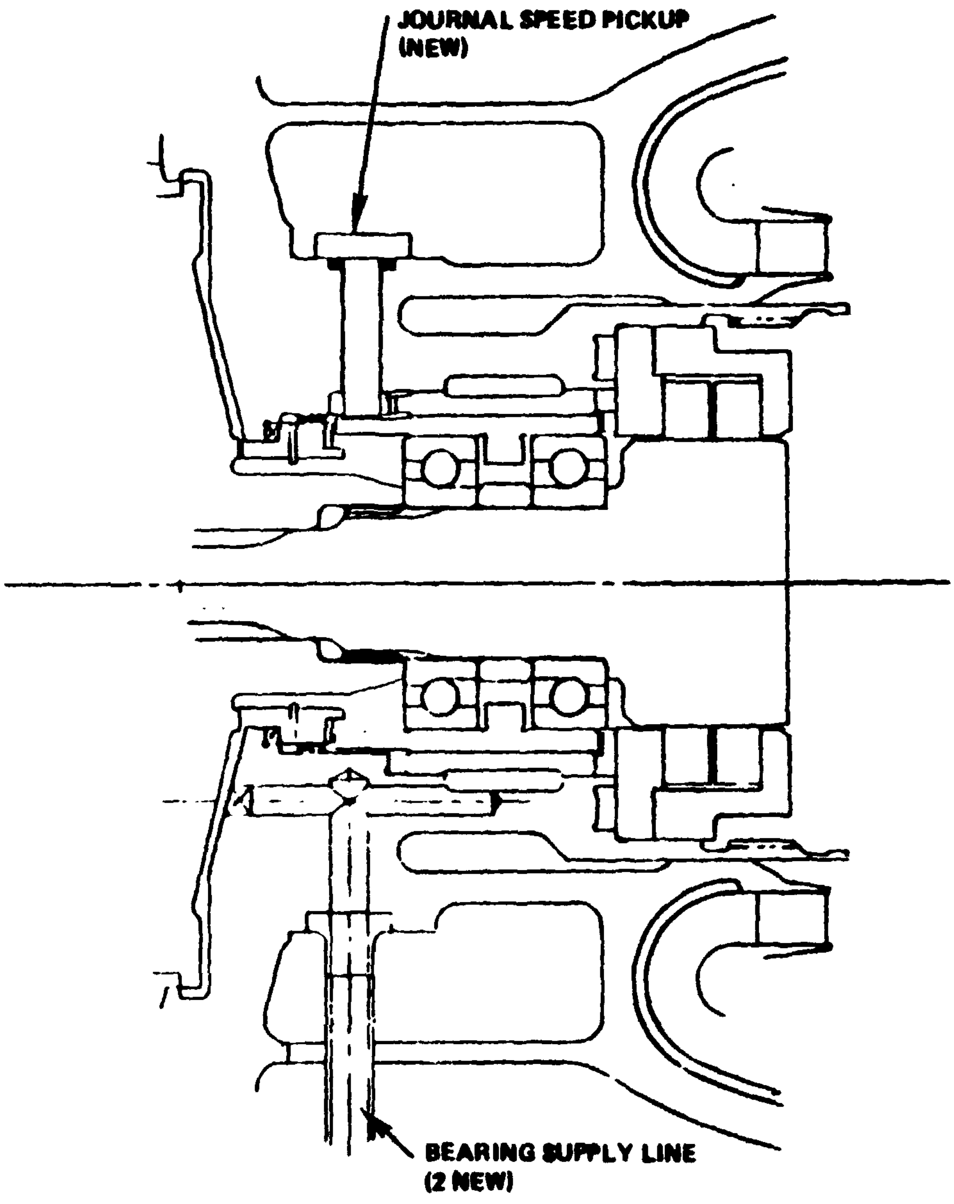

Figure 5. Turbine Bearing Design Features

(Bently) to measure cartridge (journal) rotation and the other as an interim overboard drain to ensure the balance piston sump pressure would not be excessive. Other hardware modifications to the turbine-end bearing area was to provide additional pressure taps for balance piston sump pressure and hydrostatic bearing supply manifold pressure. Bearing internal pad pressures could not be measured in the turbine-end bearing.

To accommodate axial thrust transients during start and shutdown, the turbine-end bearing journal end play was limited with Bearium axial rub ring stops on either side of the journal.

Bearing Clearance Selection

The final selection of the hydrostatic bearing diametral clearance was 0.0622 mm (0.00245 inch) at no rotational speed and 0.0305 mm (0.0012 inch) cold, and at 9948 rad/sec (95,000 rpm). The clearance change analytically derived by finite element analysis is caused by the dimensional changes of the bearing cartridge and journal due to childown, pressure load and rotational speed. These effects are shown in Fig. 6 and 7. The clearance change with speed and pressure effects is given in Fig. 8 and 9 for the pump and turbine end, respectively. The analysis used predicted fluid film pressure distribution as a function of speed. It is important to note that each component (bearing and journal) deflects due to the forces exerted upon them. This deflection is not uniform along the axial length of the bearing surface. This results in an irregular clearance variation along the bearing; these data are given in Fig. 10 and 11 for the pump and turbine-end bearings, respectively. The net result is a surface irregularity of up to 0.0229 mm (0.0009 inch). Design of a hydrostatic bearing clearance which is not irregular during operation is difficult since the irregular loading and stresses of the surfaces cannot be eliminated.

Structural Analysis

The design progressed with a structural analysis study to verify the design was adequate for full-speed operation to 9948 rad/sec (95,000 rpm). The stress analysis of the modified turbopump consisted of developing two axisymmetric finite element models of the separate bearing packages, as shown in Fig. 12. Load cases were run to account for the interference fit between the bearing outside diameter and the housing, operational temperatures, cartridge rotation to 9948 rad/sec (95,000 rpm), and pressure fields of the manifold and fluid film. This was used to predict the operating clearances previously presented and to evaluate the maximum stress levels on the bearings and cartridges. Adequate safety factors were found with the minimum values greater than 3.2 on yield and 3.6 on ultimate.

The impact to the structure due to the various modifications was also analyzed. On the pump end of the turbopump, the minimum limiting safety factor of 1.86 on pressure stress was determined for the loading adjacent to the inside diameter of the bearing cavity adjacent to the supply tube. Later, as the components were reviewed during modification, the analysis set a pressure limit of 1300 psig in the hydrostatic bearing manifold for a limit safety factor of 1.4. All other

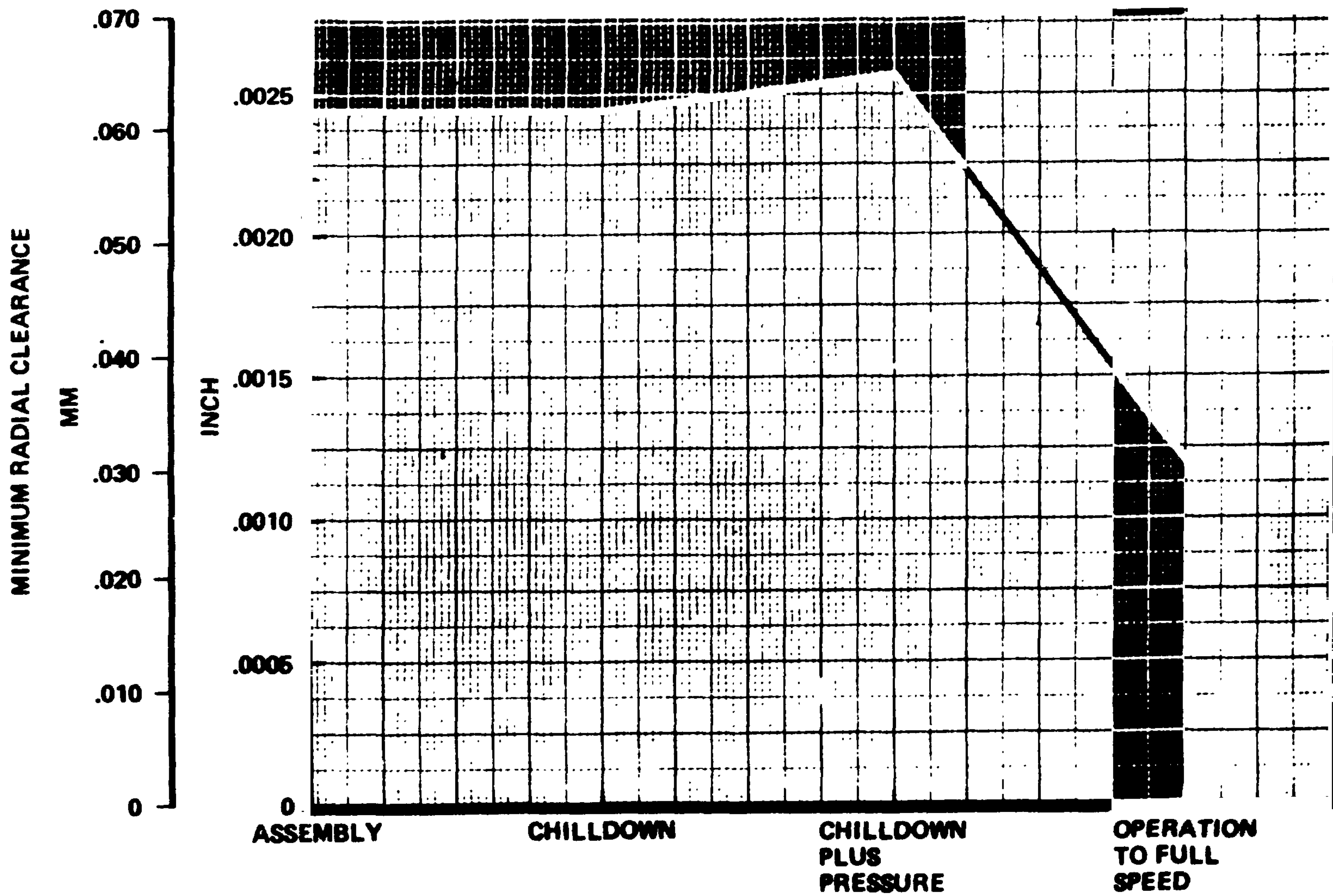

Figure 6. Minimum Radial Clearance vs Load Components - Pump End

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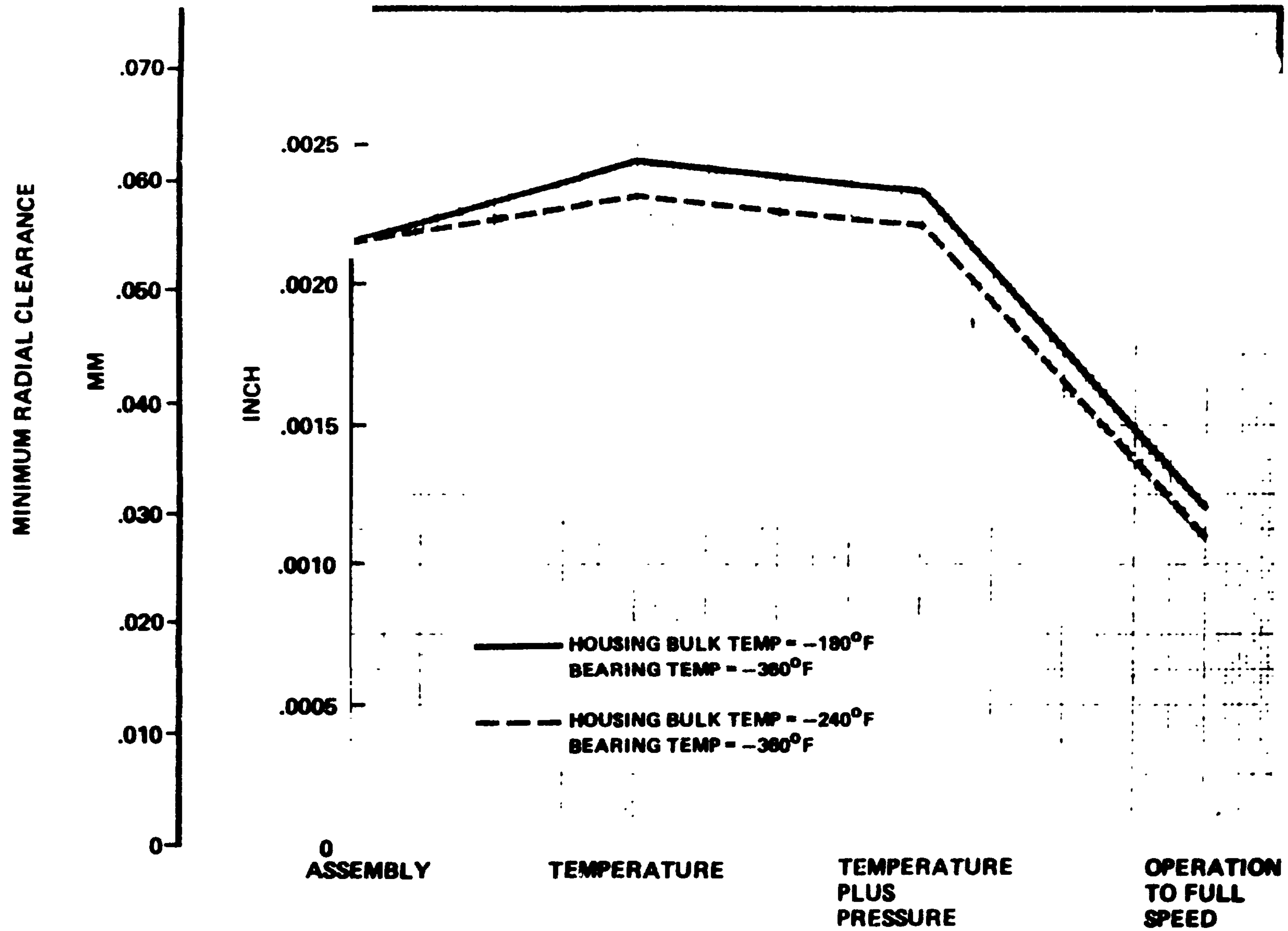

Figure 7. Minimum Radial Clearance vs Load Components - Turbine End

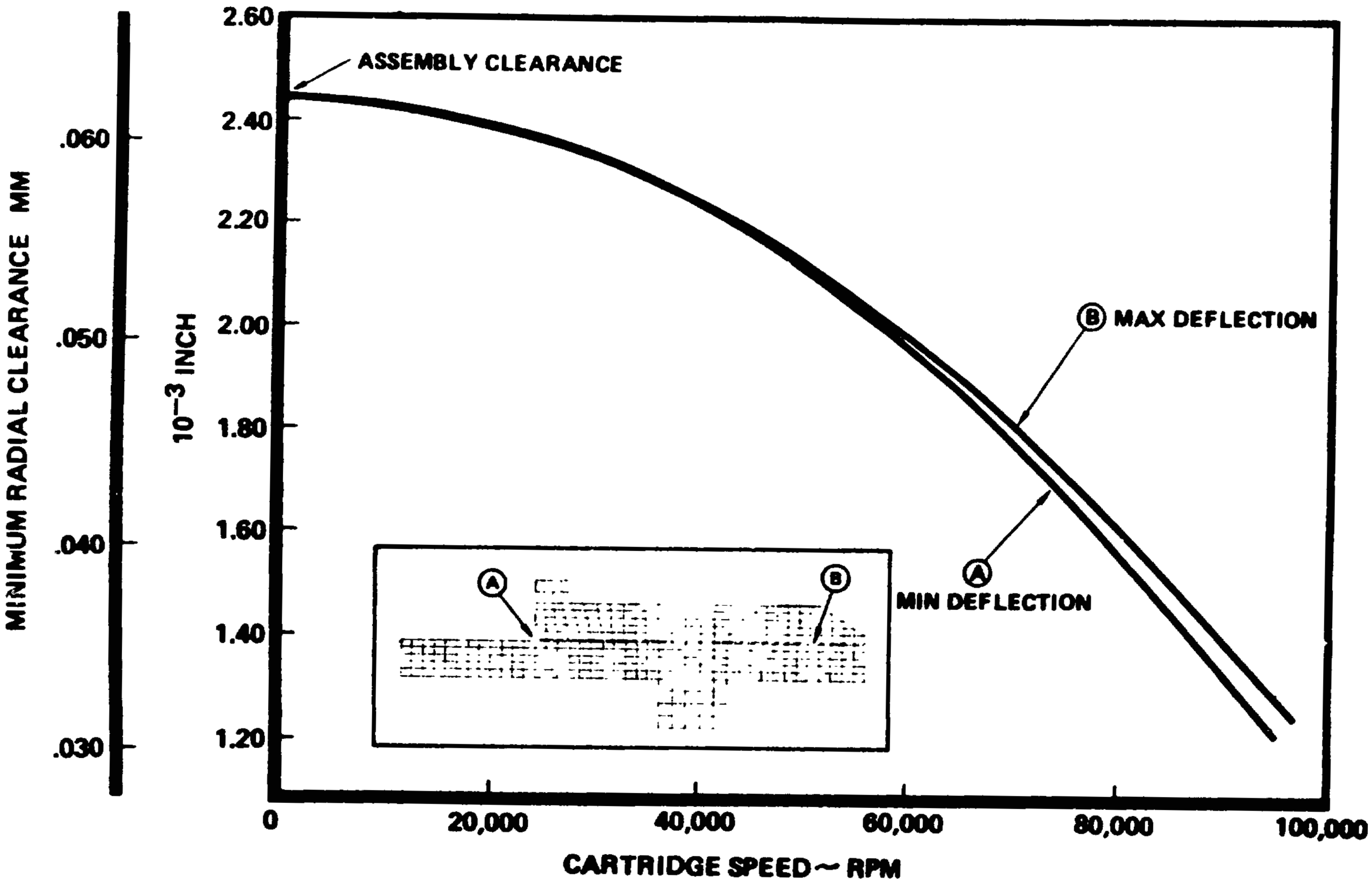

Figure 8. Minimum Radial Clearance vs Cartridge Speed - Pump Side

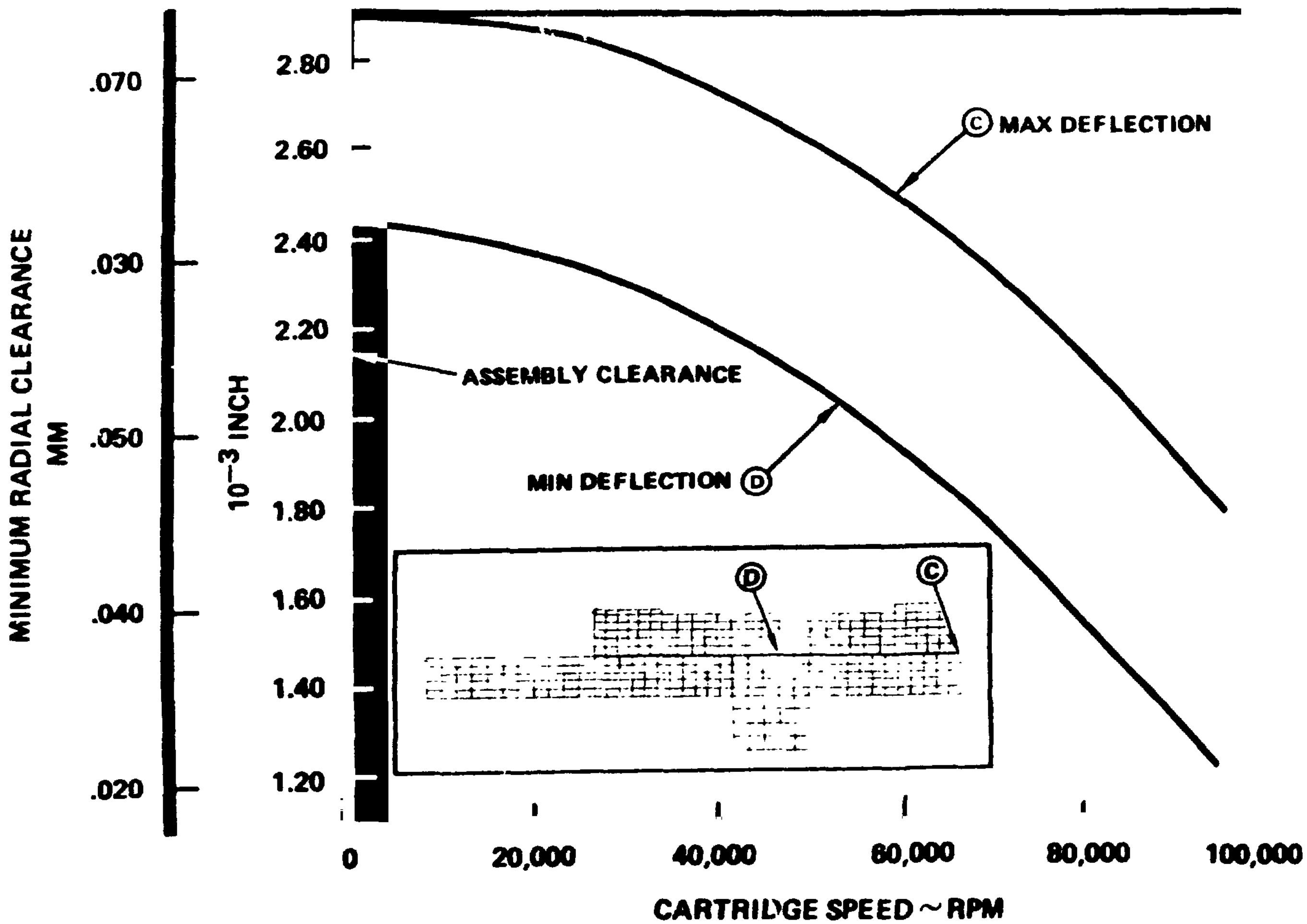

Figure 9. Minimum Radial Clearance vs Cartridge Speed - Turbine Side

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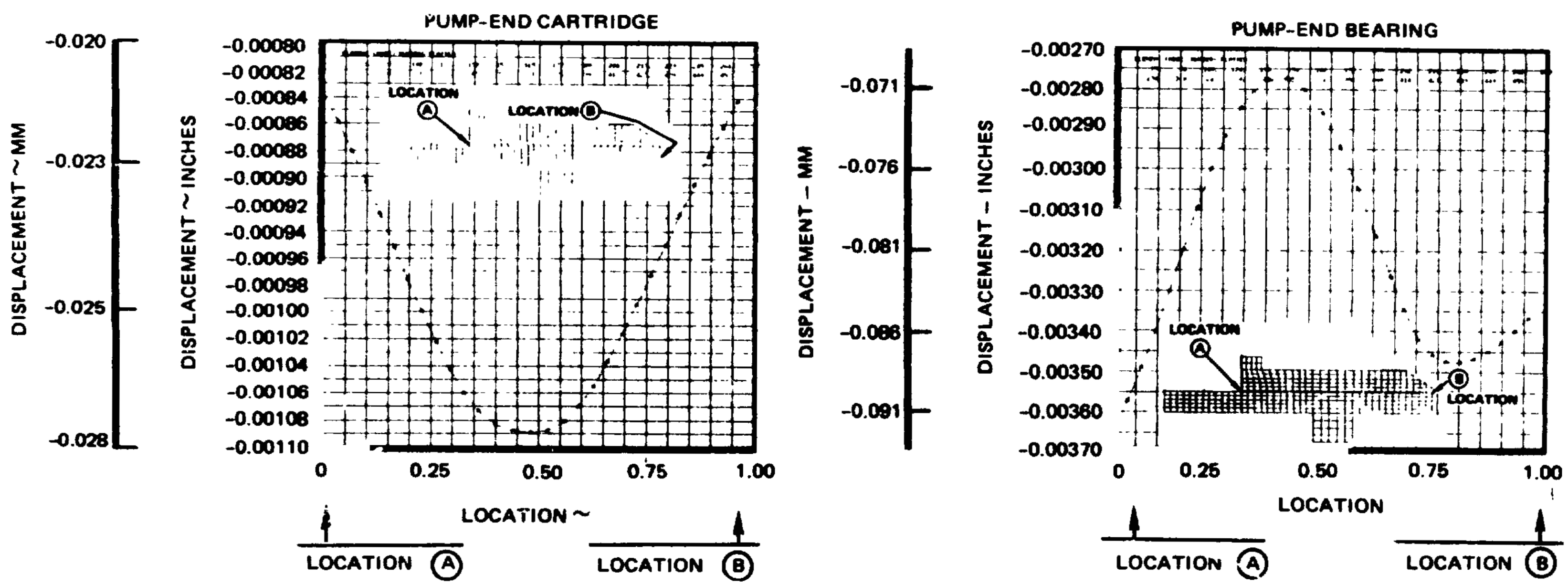

Figure 10. Pump-End Cartridge and Bearing Ope[illegible] -flections

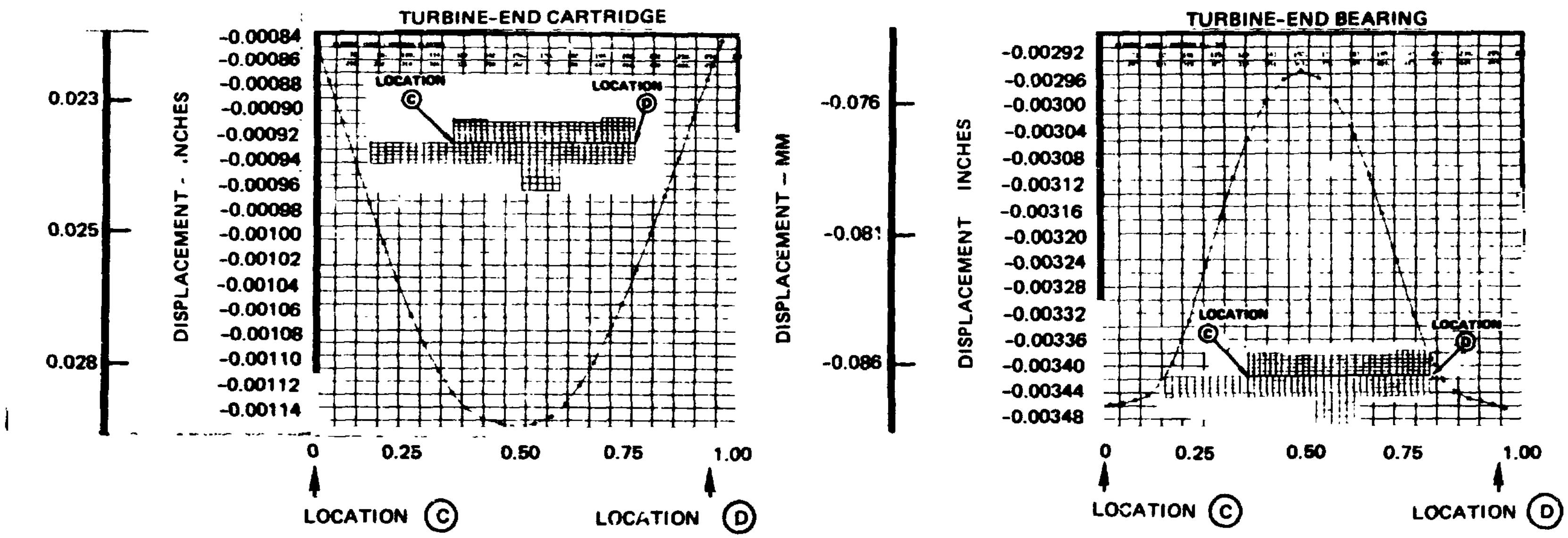

Figure 11. Turbine-End Cartridge and Bearing Operating Deflections

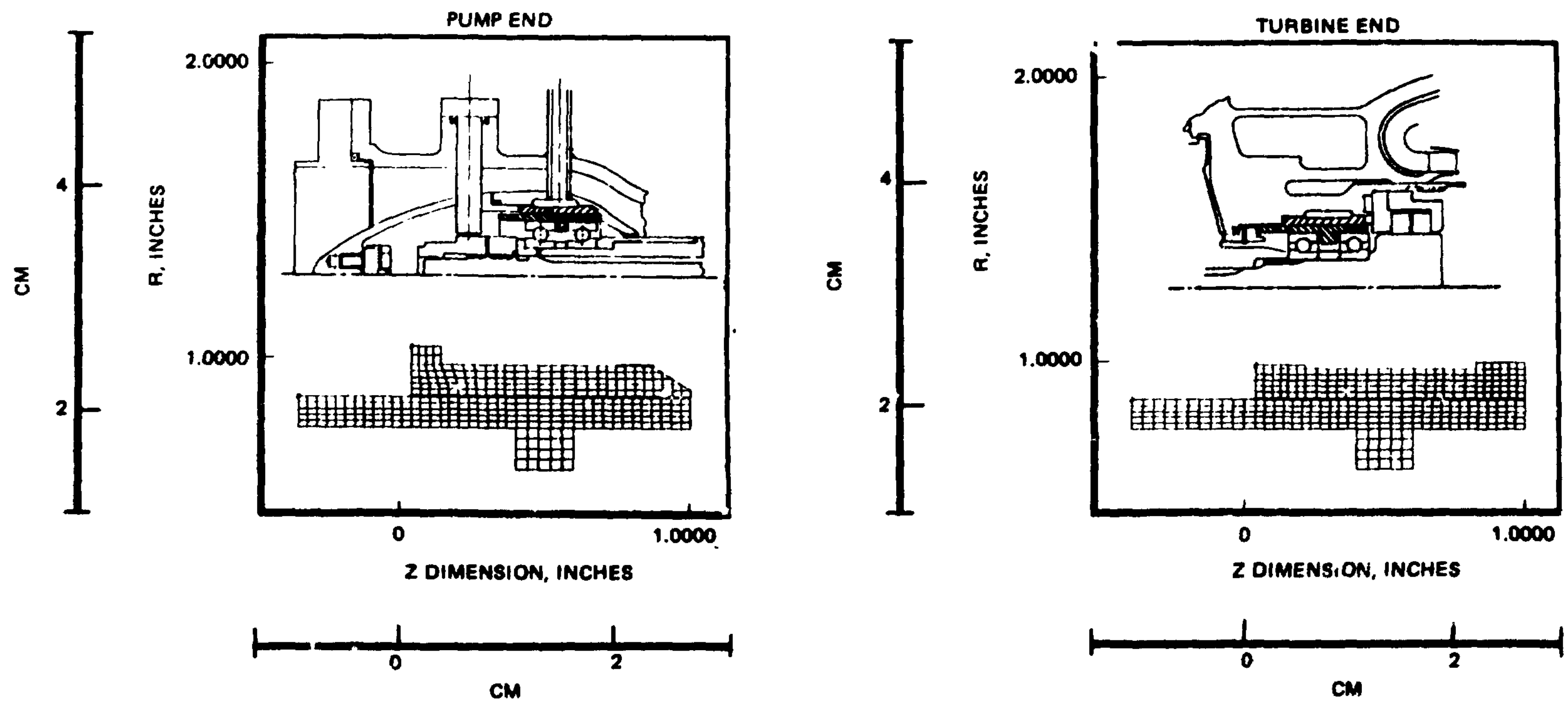

Figure 12. Finite Element Model Pump and Turbine Ends

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areas of the pump bearing and inlet modifications showed safety factors greater than 10. Analysis of the modification to the turbine-end bearing indicated the minimum ultimate safety factor of 2.9 on pressure stress due to the removal of material on the inside diameter of the bearing cavity. All other areas of stress in the turbine-end area also were very satisfactory.

Ball Bearing Stresses

A concern was expressed at the start of the design study that the ball bearing might be overstressed as the outer race rotated with the inner race and balls and might incur loads greater than the ball Brinell capacity. Further concern was whether the armalon cages would be strong enough to carry the high rotational speeds. The results of the bearing analysis indicates the ball bearing is not overstressed at the maximum cartridge speed. The ball outer race stress was calculated as a function of outer race speed with an axial preload of 445 N (100 pounds). The results are shown in Fig. 13 and indicate the outer race stress at maximum speed at 260,000 N/cm^2 (377,000 psi) whereas the Brinell capacity of the balls is 344,721 N/cm^2 (500,000 psi). Additionally, the analysis indicated the cage would not be damaged by cartridge speed and the net diametral cage-to-race clearance (chilled at speed) would range from 0.0432 to 0.1956 mm (0.0017 to 0.0077 inch). Ball bearing B1 life was calculated as a function of outer race speed for an inner race speed of 9948 rad/sec (95,000 rpm) and a preload of 445 N (100 pounds). The results (Fig. 14) indicate B1 life with no cartridge rotation is 23 hours and the minimum B1 life of 6.5 hours occurs at a cartridge speed of 6283 rad/sec (60,000 rpm). The curve also indicates that cartridge speed above 9477 rad/sec (90,500 rpm) greatly improves B1 life.

A detailed design review was conducted at NASA-LeRC on 18 December 1980. The review indicated that the modifications required were acceptable as developed and that work could proceed on the fabrication of the components. All the dimensions of the design were fixed at that time except for two values: the desired hydrostatic bearing operating clearance and the orifice size. A necessity for additional dynamic analysis was evident before the clearance could be established. This analysis will be detailed in a later section of this report. This decision did not, however, hinder the turbopump modification and fabrication activities that followed.

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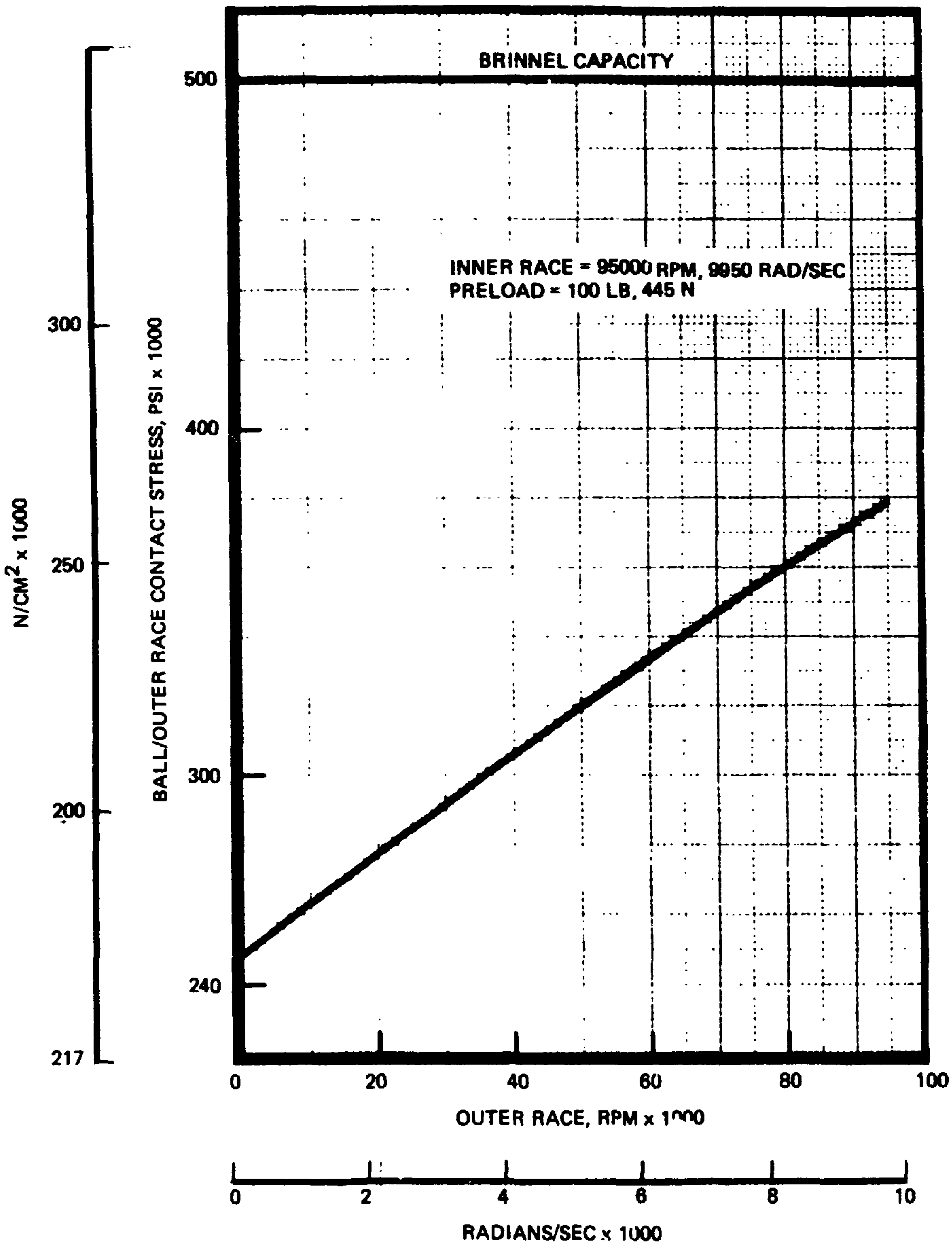

Figure 13. Ball Bearing Stress in Hybrid Bearing

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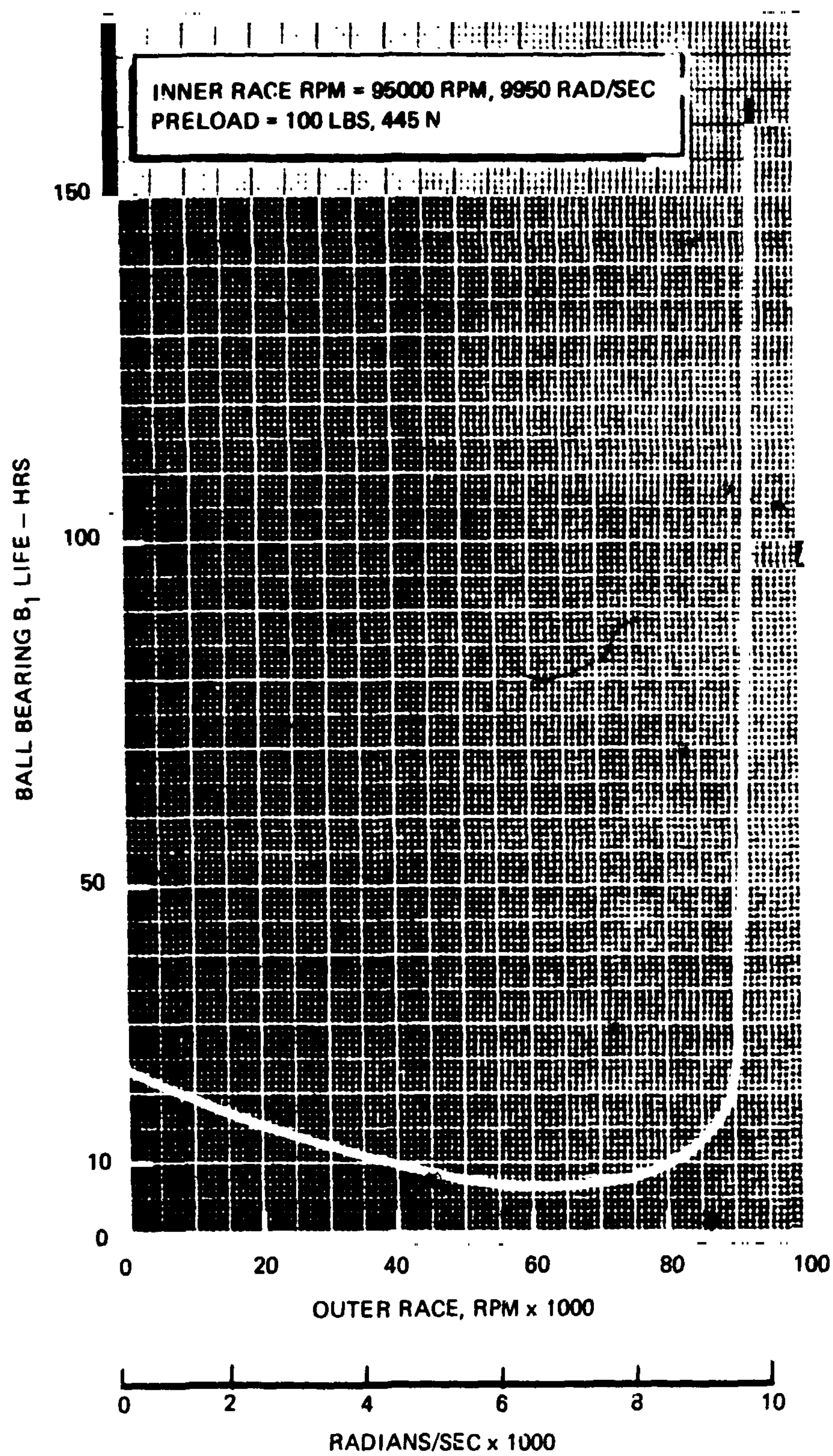

Figure 14. Ball Bearing Life With Hybrid Bearing

TURBOPUMP MODIFICATION AND ASSEMBLY

Modification

The detail design review approval allowed the modification and fabrication of hardware to begin. The design required that many components be fabricated or modified. These components are listed in Table 1 for both the turbine-end and pump-end bearings. The number of items per build and the number to be fabricated are listed. Spares were considered necessary on some components since it was expected that the hydrostatic bearings may need replacement or rework during the testing. The parts shown for modification or fabrication are correlated with the component part numbers in Fig. 15 and Appendix A. Major modifications to the existing components are given in Table 2.

The fabrication of matching components (bearings and journals) had to be very closely controlled. A target value of 0.0610 mm (0.0024 inch) static, ambient radial clearance on the hydrostatic bearings required very high tolerances be held as the bearing components were machined and assembled. The bearings on the pump end had an added complication due to the requirement of bearing pad pressure taps (Fig. 16). To accomplish this, holes to the bearing pads were drilled into the rough machined bearing. Then pressure transfer tubes were vacuum furnace brazed into the bearing in a combined brazing and heat treat operation. After brazing, the bearing was machined to final fit dimensions and the inside diameter was silver plated to given requirements. The bearing was then shrunk fit into the pump inlet housing. The inlet housing had previously been modified to accommodate the bearing as well as machined and welded to provide the hydrostatic bearing supply lines and instrumentation ports. After the shrink fit, the bearing inside diameter was machined to concentricity with the inlet housing and to the diameter of 44.303 +0.010, -0.000 mm (1.7442 +0.0004, -0.0000 inch). The cartridge for the pump-end bearing was then match ground for a thin, dense chrome plating diameter to provide 0.0610 ±0.0076 mm (0.0024 ±0.0003 inch) radial clearance. The final configuration of the pump-end bearing in the housing is given in Fig. 17.

After final machining of the pump-end bearing in place in the housing, the three bearing pad pressure lines were welded to transfer tubes and routed radially out through a larger transfer line. This was to protect them from the pump inlet flow. They were then sealed by brazing in the transfer tube outside the inlet housing body. Figure 18 shows the two bearing supply lines (largest tubes), the bearing pad supply pressure transfer tube (2 o'clock), the eight equally spaced bearing supply tapoff tubes, and other pressure taps and drains. The eight equally spaced bearing supply tapoff holes were designed to minimize the radial pressure effects on the first-stage impeller front shroud. The flow was tapped off from just inside the impeller tip with the tapoff holes chamfered in the flow direction to minimize the entrance losses (Fig. 19). For the recirculation tests, the flow was tapped off to external lines and then routed back into the two large bearing supply lines shown.

The inlet flange P/N 9R0015131 (Appendix A) provides an enclosing faired section for the pump-end bearings (Fig. 20). The modification to this part consisted of

TABLE 1. DESIGN AND MODIFICATION REQUIREMENTS

PART DESCRIPTION	PART NUMBER	PROCUREMENT	QUANTITY	
			PERBUILD	FABRICATE
• TURBINE END				
• CARTRIDGE	9R0015132	NEW	1	2
• BEARING	9R0015129	NEW	1	2
• NUT, LOCK, BALANCE PISTON	9R0015130	MOD	1	1
• RING, RUBBING - LOW PRESSURE	9R0015127	MOD	1	1
• RING, RUBBING - FORWARD	9R0015137	NEW	1	2
• RING, RUBBING - AFT	9R0015126	NEW	1	2
• LOCK, NUT - BALANCE PISTON	RS009633	MOD	1	1
• SPEED PICKUP, CARTRIDGE	9R0015134	NEW	1	2
• TURBINE HOUSING	9R0015123	MOD	1	1
• PUMP END				
• CARTRIDGE	9R0015125	NEW	1	2
• BEARING	9R0015128	NEW	1	2
• SPEED NUT	9RC011556	MOD	1	1
• AXIAL BENTLY	9R0015133	NEW	1	2
• RADIAL BENTLY	9R0015135	NEW	2	3
• SPEED PICKUP, CARTRIDGE	9R0015134	NEW	1	1
• INLET HOUSING	9R0015124	MOD	1	1
• INLET FLANGE	9R0015131	MOD	1	1
• SHIM PLATE, BENTLY	9R0015136	NEW	1	1

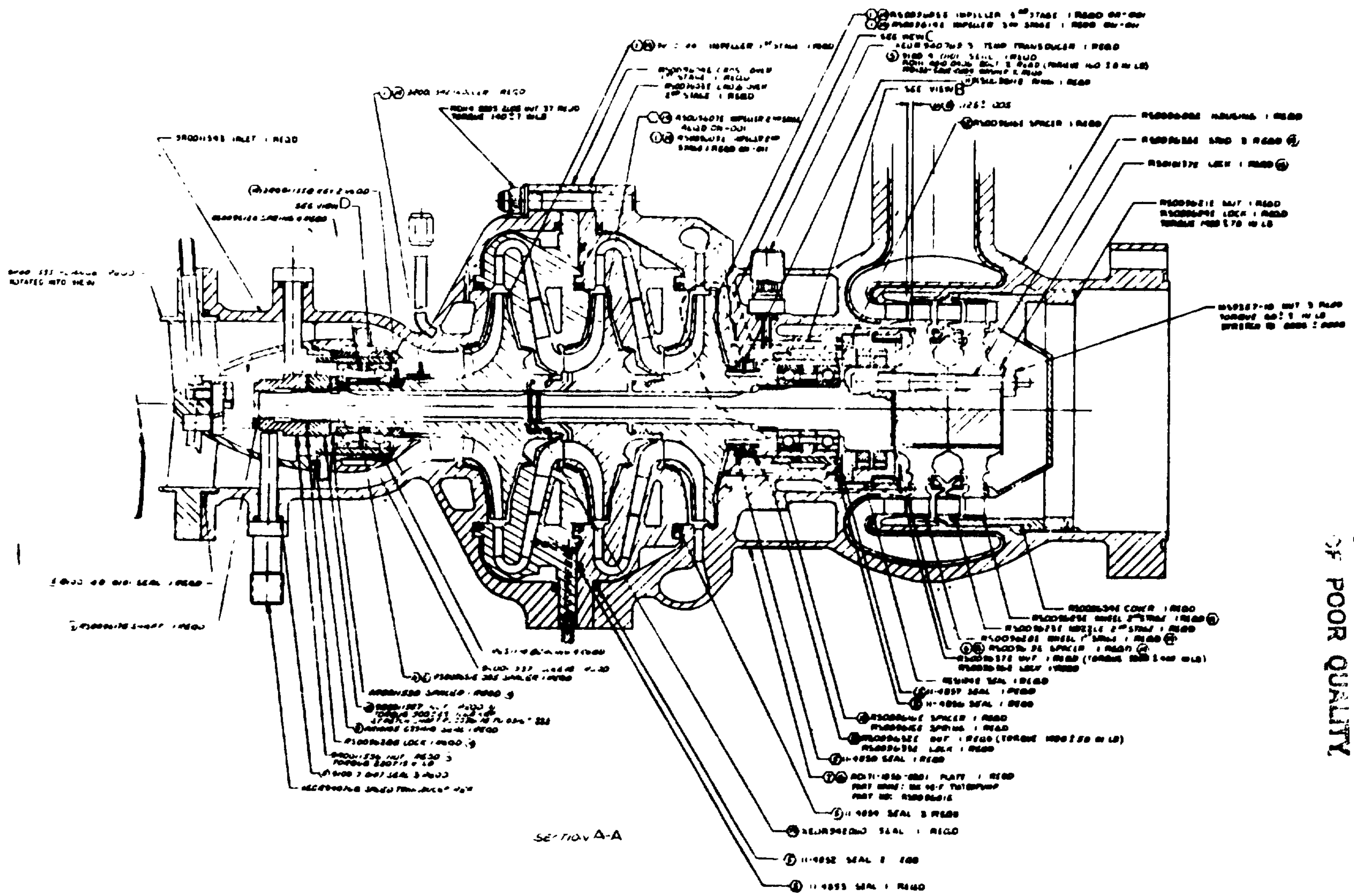

Figure 15. Hybrid Bearing Turbopump

TABLE 2. MAJOR COMPONENT MODIFICATION REQUIREMENTS

TURBINE HOUSING: INCONEL 718 AND HAYNES 188

- MACHINE FOR SUPPLY LINE, MANIFOLD, AND BEARING
- MACHINE FOR CARTRIDGE EXTENSION
- MACHINE FOR PRESSURE TAPS - WELD FITTINGS
- PLUG WELD AND CLEAN UP SURFACES
- MACHINE FOR CARTRIDGE SPEED PICKUP - WELD FITTING
- SHRINK FIT BEARINGS - FINAL MACHINE IN PLACE

INLET HOUSING: INCONEL 718

- MACHINE FOR EIGHT FIRST-STAGE IMPELLER FRONT SHROUD FLOW TAPOFFS
- MACHINE FOR TWO SUPPLY LINES, MANIFOLD, AND BEARING
- MACHINE FOR MANIFOLD PRESSURE TAP - WELD FITTING
- MACHINE FOR TWO CARTRIDGE SPEED PICKUPS - WELD FITTINGS
- WELD ALL PRESSURE TAP AND SUPPLY LINE FITTINGS
- SHRINK FIT BEARINGS - FINAL MACHINE IN PLACE

INLET FLANGE: INCONEL 718

- MACHINE MOUNT FOR AXIAL POSITION BENTLY
- DRILL IN TWO VANES ADDITIONAL BEARING FLOW DRAINS - WELD FITTINGS
- DRILL IN ONE VANE, LINE FOR AXIAL BENTLY CABLE, SUMP PRESSURE TAP

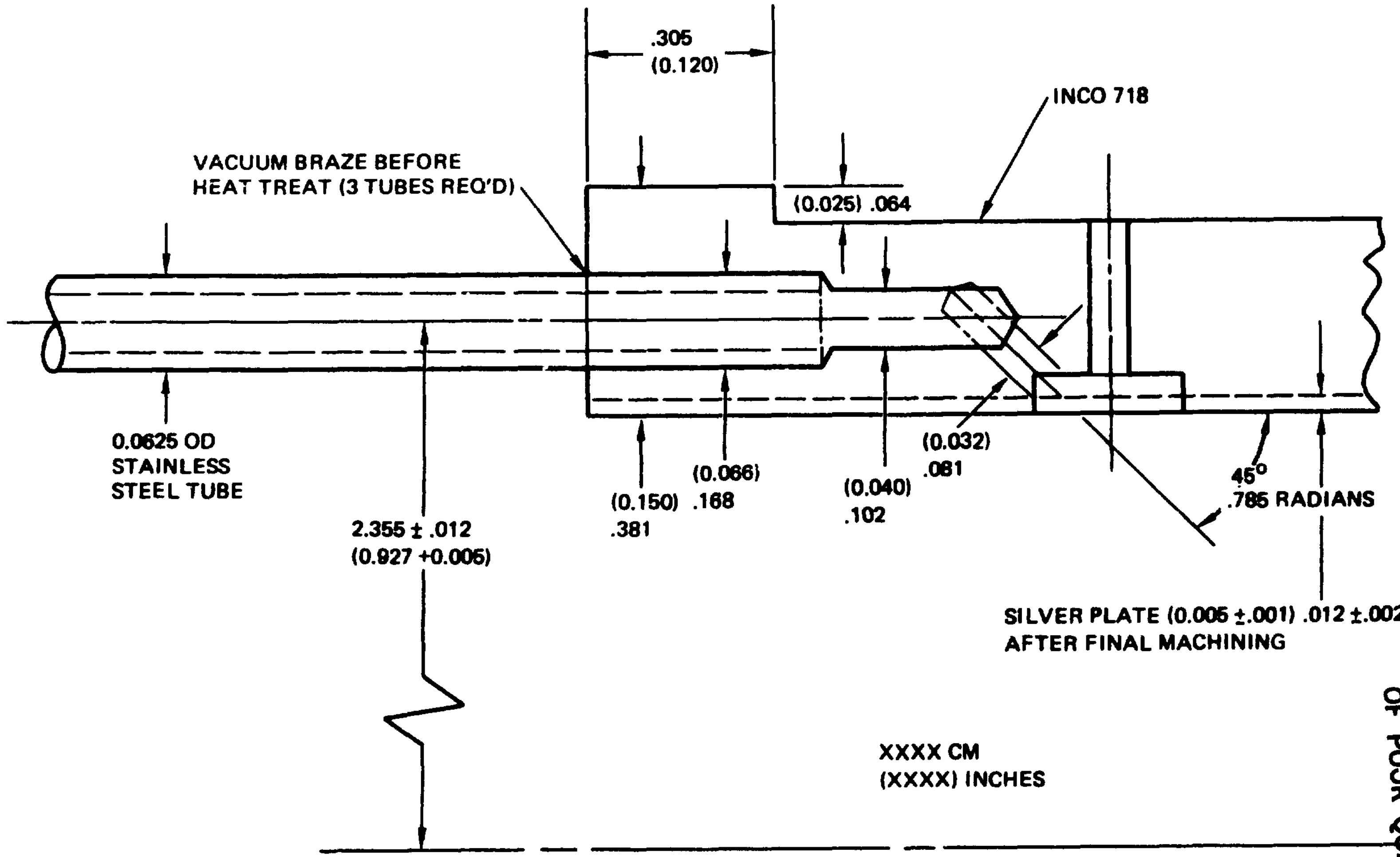

Figure 16. Instrumentation Line for Bearing Recess Pressure

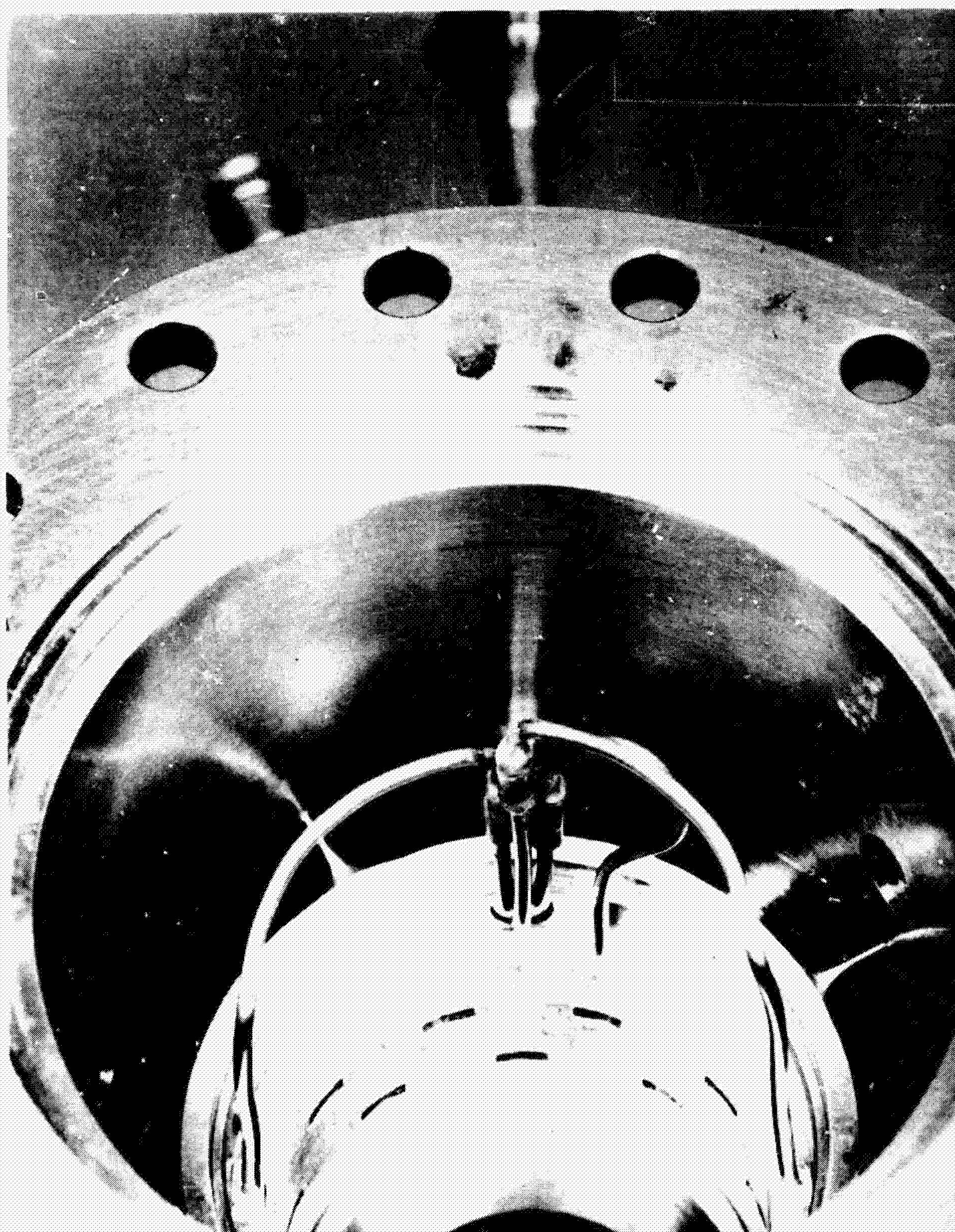

Figure 17. Pump Inlet Housing with Hydrostatic Bearing

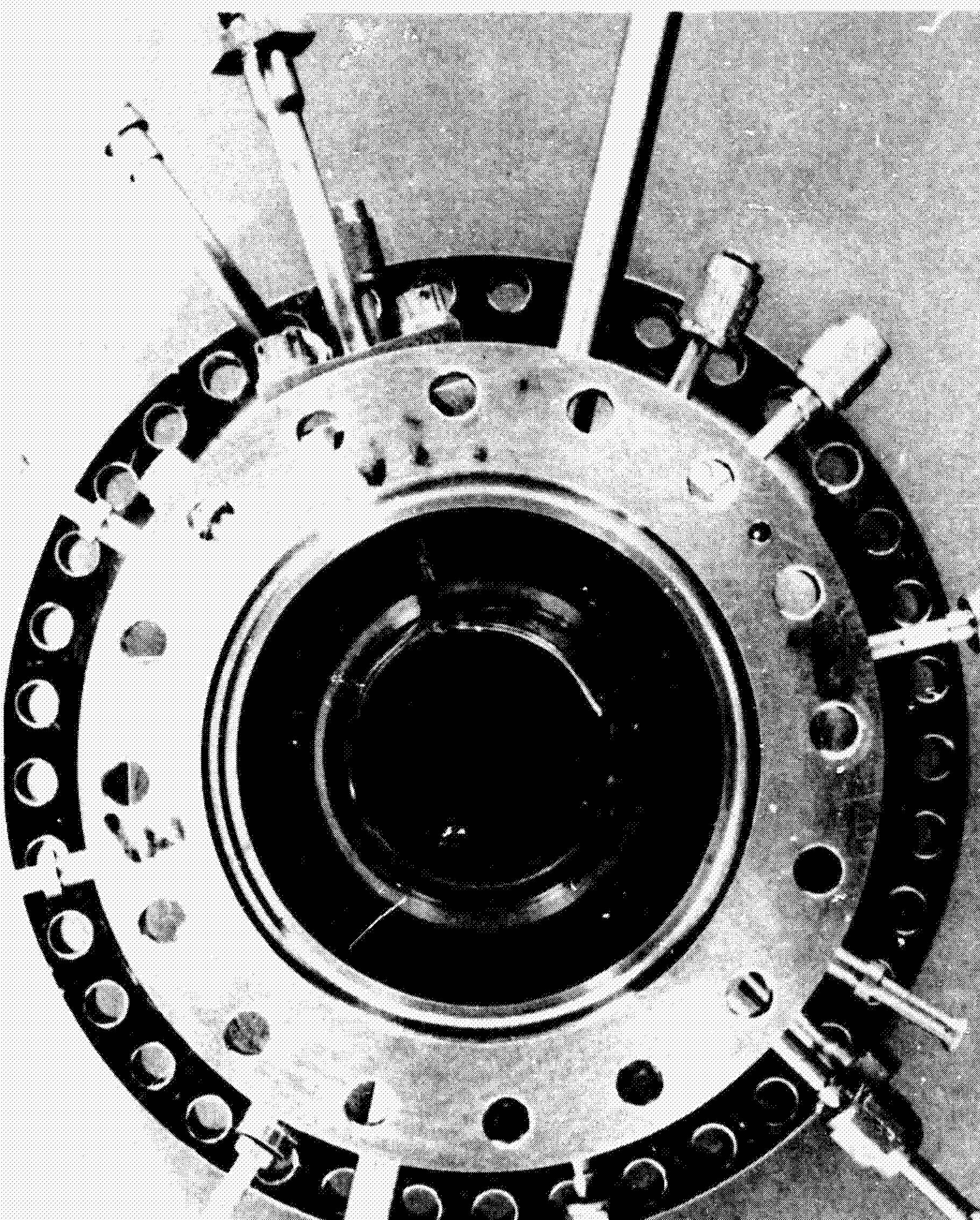

Figure 18. Pump Inlet Housing After Modification

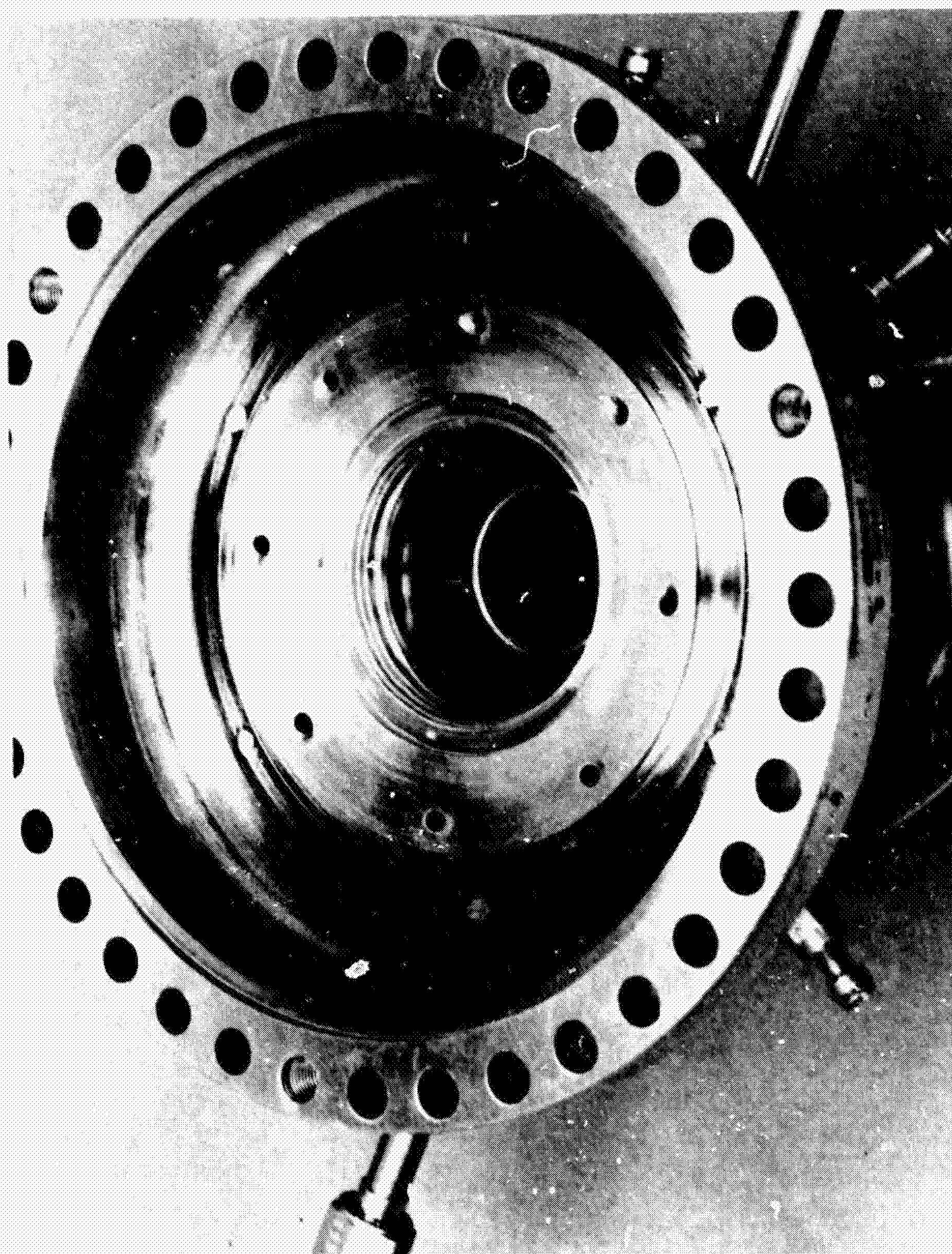

Figure 19. Pump Inlet Housing with Eight Bearing Supply Tapoff Holes

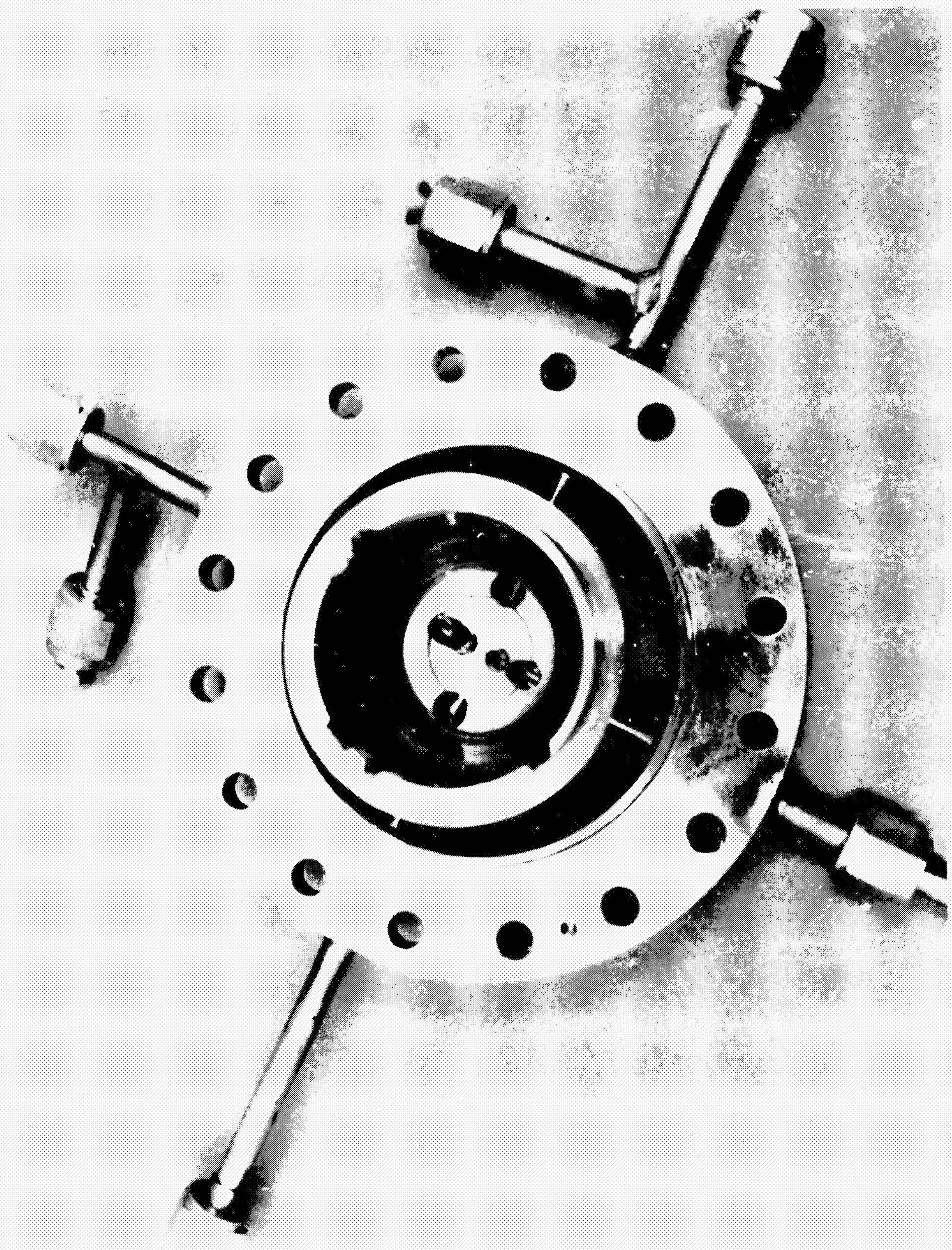

Figure 20. Pump Inlet Flange Modified for Flow Drains and Instrumentation

drilling holes through three of the four radial vanes for use in increasing the drain flow area for the bearing sump, as a transfer line for the wiring to the proximity detector (Bently) for shaft axial position measurement and a pressure measurement for the bearing sump. The center inside segment of the nose piece was also machined to mount the axial proximeter probe.

The turbine housing modifications were given in Table 2. After all the modifications were made, including the machining and welding, the bore for the hydrostatic bearing was final machined to concentricity with the critical pilot points on the housing. The bearing was then shrunk and press fit into the housing. Final machining of the bearing inside diameter was completed. Figure 21 shows the turbine housing looking from the third-stage impeller side. The outer diameter shown is the balance piston high-pressure orifice area and the entrance opening of the diffuser. The hydrostatic bearing with its characteristic pressure pads are shown aft of the balance piston aft face. The threaded section in the bore is used to hold the bearium low-pressure orifice rub ring for the balance piston which was not installed for the photo. A cross section for better orientation of the photo can be seen in Fig. 5.

The complete rotor assembly of the hybrid hydrostatic/ball bearing configuration is shown in Fig. 22. The basic components shown, starting from the pump inlet end, are as follows:

- Instrumentation nut
- Hybrid bearing - pump end
- Inducer
- First-, second-, and third-stage impellers
- Hybrid bearing - turbine end
- Turbine hot-gas seal surface - shaft
- First- and second-stage turbine wheels

Figure 23 shows the pump-end bearing and rotor assembly. The bearing cartridge has eight 0.762 mm (0.030 inch) slots equally spaced about its circumference on the inlet end for use with a radial position proximeter to record cartridge speed. The instrumentation nut at the shaft end has three distinct features worth noting. The end section of the nut has an axial slot cut into the material encompassing 0.785 radians (45 degrees) of arc and 0.152 mm (0.006 inch) deep. This is used to calibrate the shaft axial position on the target ring shown for the axial proximeter detector mounted in the inlet flange (Fig. 4). Immediately aft of the axial proximeter ring is a four-sided section used as a balancing and torquing surface and also in conjunction with a radially mounted shaft magnetic speed counter to monitor shaft speed (Fig. 3). The four flats per revolution provide a good sine wave signal for speed counting. Just aft of this is a circular section with a calibration slot cut into the circumference for an arc of 0.785 radians (45 degrees) and 0.066 mm (0.0026 inch) deep. This axial section was used in conjunction with two orthogonally mounted radial proximeters to measure the shaft radial motion (Fig. 4). Aft of the instrumentation nut is the

Figure 21. Turbine Housing with Hydrostatic Bearing in Position

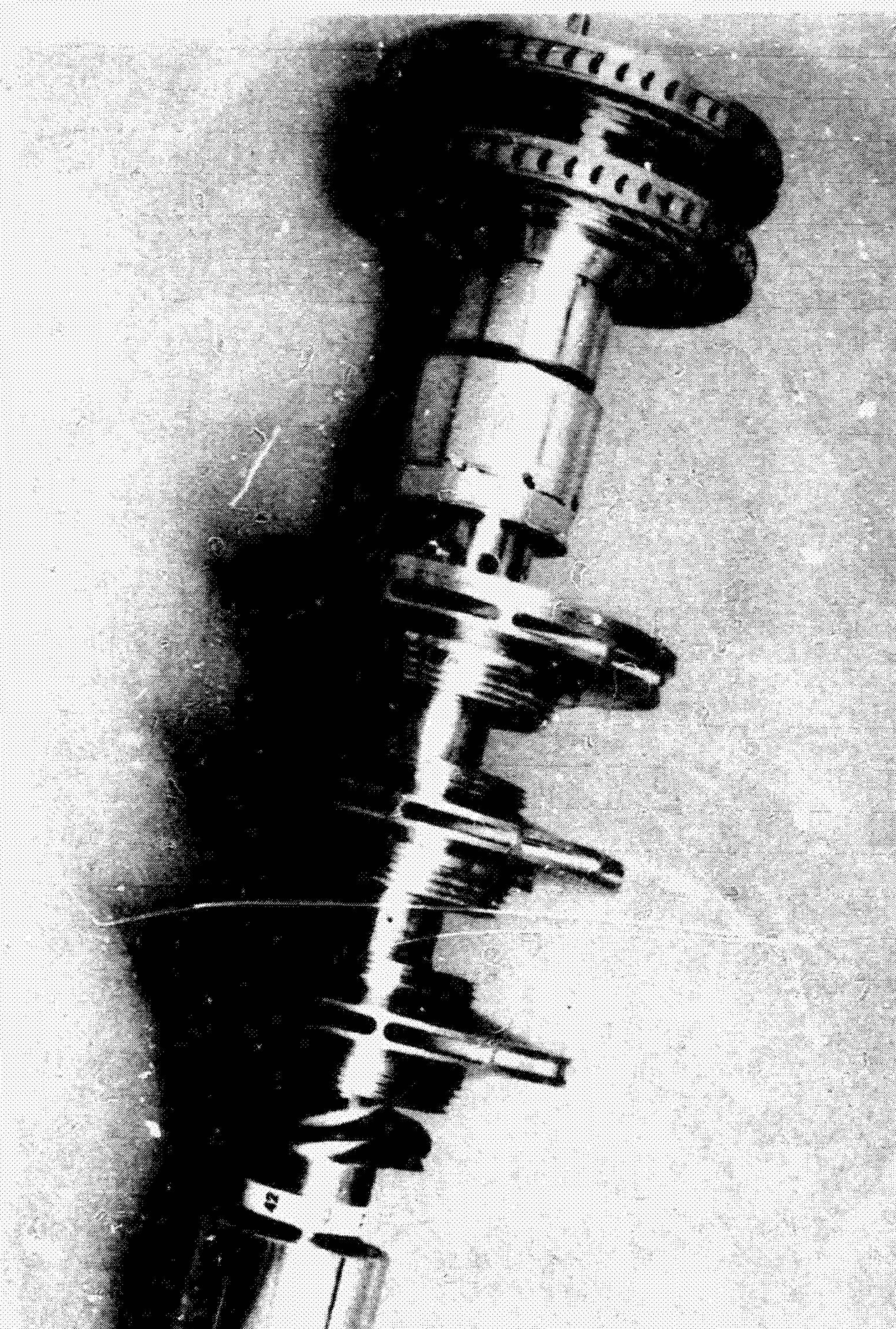

Figure 22. Mark 48-F Turbopump Rotor Assembly with Hybrid Bearings

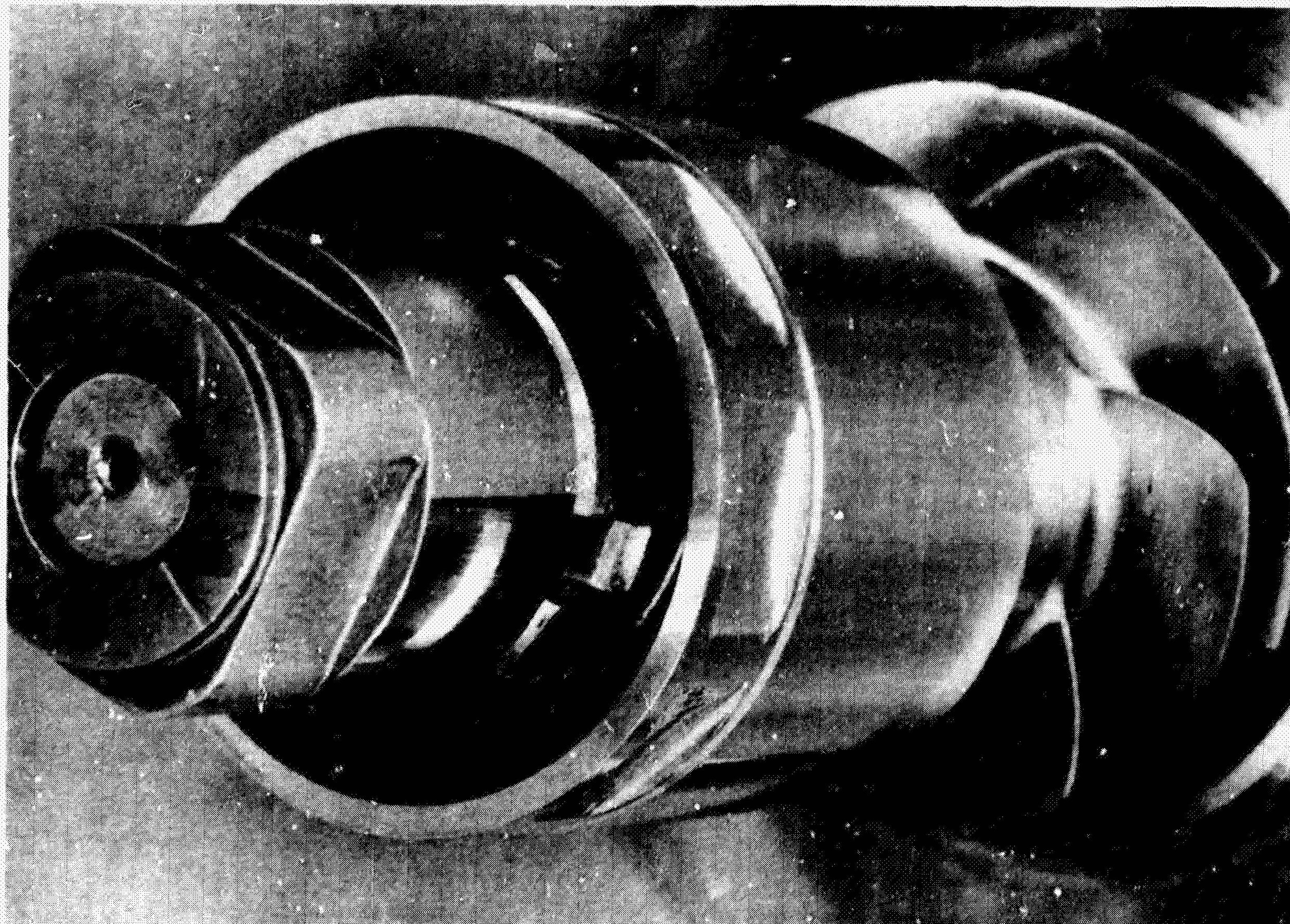

Figure 23. Pump End of Rotating Assembly - Instrumentation Nut, Cartridge, and Inducer

ball bearing locking nut. This nut also preloads the rotor assembly stackup through the impeller hub stack with a load of approximately 40032 N (9000 pounds) ambient.

The turbine-end hydrostatic bearing cartridge mounted on the rotor assembly between the first-stage turbine wheel and the third-stage inducer is given in Fig. 24. The cartridge is shown with eight equally spaced slots for cartridge speed monitoring. Adjacent to the slots are eight holes drilled at 0.785 radians (45 degrees) off the radial and axial axes. These are to allow the hydrostatic bearing flow to discharge into the bearing cavity if the axial position of the shaft were to close off the end clearance between the cartridge and the front axial thrust stop. Also note the set of holes in the third-stage impeller hub. These are used for returning the balance piston and hydrostatic bearing flows back to the second-stage impeller inlet.

All modifications were made to the turbopump hardware. Major problem areas that had to be closely monitored and required special care were distortion possibilities of the housings from machining and welding, close tolerances in matching hydrostatic bearing clearances combined with silver and chrome plating processes, and shrink fits on the bearings. In general, the modifications were satisfactory due to expert professional support in the Rocketdyne machine and weld and plating facilities and several outside vendors who fabricated the cartridges and other components.

Assembly - Rotordynamic Balancing

The assembly of the turbopump began with the balancing of the rotor assembly. The balancing of the rotor assembly was considered extremely important to the success of the program. In addition to the complexity of balancing the rotating assembly, which includes one inducer, three impellers, and two turbine wheels, is the problem encountered with balancing the outer races and cartridge journal rings for the hydrostatic bearing. A major problem encountered is that relative angular position of the cartridge with the rotating assembly changes continually. For satisfactory operation at all speeds and chilled conditions, there is diametral clearance required between the bearing outer races and the cartridge which adds to the complexity. Therefore, it was necessary to balance both components individually to a high tolerance prior to balancing the complete assembly. Proper care was also taken to control total indicated runout (TIR) on the cartridge inside diameter and bearings were selected with minimal TIR on the outer races.

The balancing proceeded with detail balancing of the individual cartridges on an arbor. Only minor corrections were required and the assembly of the cartridge onto the arbor was changed to verify balance corrections were not assembly related. The balancing of the rotor assembly began using a set of slave bearings. The basic procedures used were those developed through several previous builds

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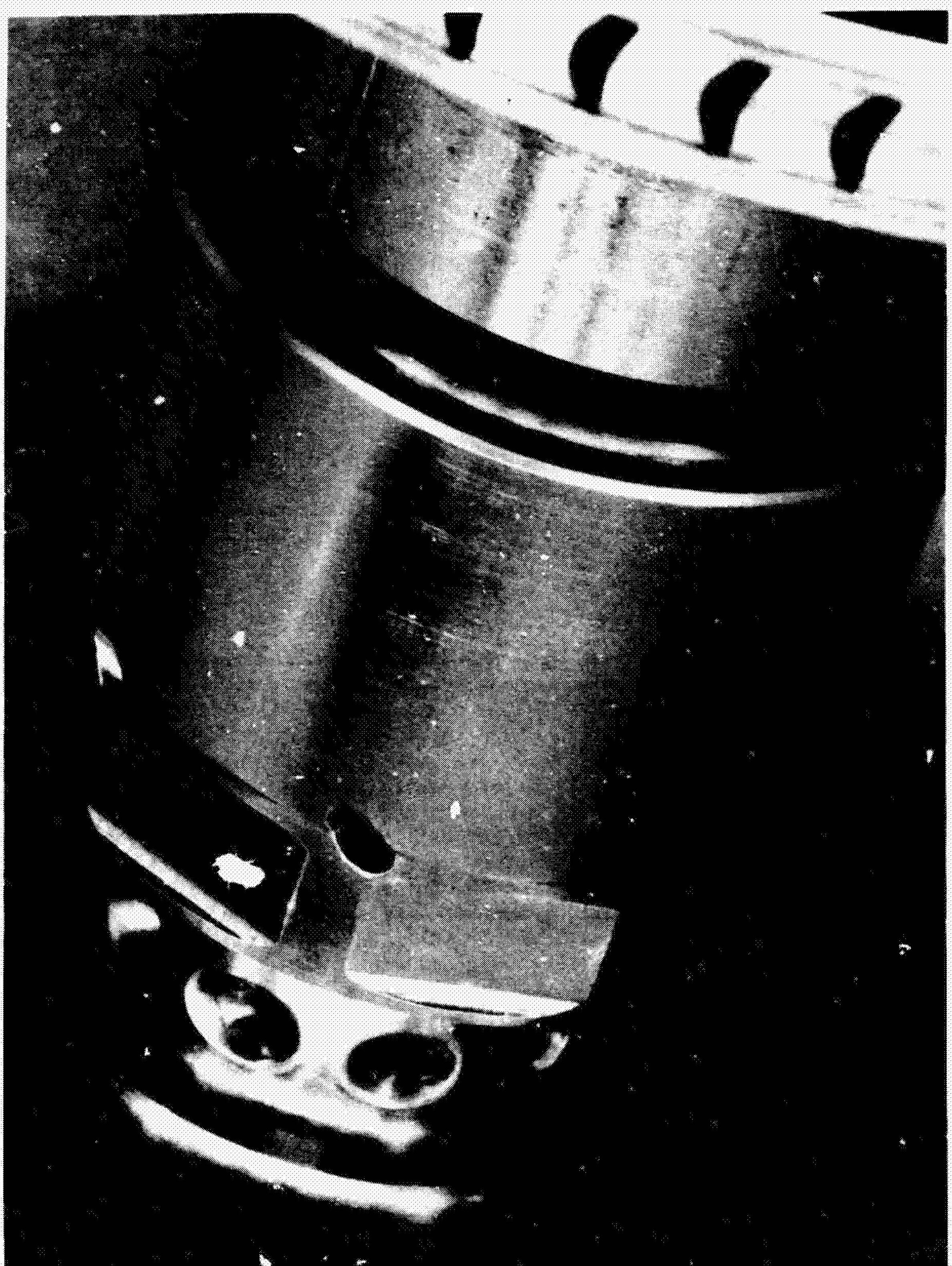


Figure 24. Turbine-end Bearing Cartridge Mounted on Rotor Assembly

(Fig. 25). The procedure is a step-by-step balance of the rotating assembly as components are added to the rotor until all components are assembled. The first step is to assemble the first- and third-stage impellers separated by a previously balanced spacer arbor and obtain correction requirements for the first and third impeller planes. Next, the second-stage impeller is installed and correction determined for the second-stage impeller plane. Next, the first and second turbine wheels are added and corrections are made for these planes. Lastly, the instrumentation nut is added and corrections made for that plane.

This process (described above) was preceded by a series of builds to determine the rotor component stackup which resulted in the minimum TIRs of each component (Fig. 26). The angular positioning of each component was matchmarked so that the assembly position would be duplicated every time. The balancing process described was then repeated several times to determine if the correction requirements repeated. At this time, it was found that the procedure for stretching the shaft center bolt and torquing the locking nut had to be modified. In this assembly, the shaft bolt is stretched on a tensile machine to 60048 N (13500 pounds) for a shaft stretch of approximately 0.813 mm (0.032 inch). In previous builds, the locking nut torque of approximately 3389 N-cm (300 in.-lb) was applied prior to releasing the shaft bolt. This resulted in a final net combined compressive load through the impeller stack of around 40032 N (9000 pounds). It was found however, that the added torque of the locking nut was responsible for causing variable TIR in the rotor assembly components after release by the tensile machine. As a result, the locking nut torque was reduced to 565 N-cm (50 in.-lb). This resulted in a much smaller variation in TIR after rotor assembly loading. Structural analysis indicated the change was acceptable and impeller hub compression preload requirements were satisfied. The after release shaft bolt stretch was measured at 0.452 mm (0.0178 inch).

The repeatability of the rotor balance between builds was found to be within 9×10^{-3} kg-mm (0.2 gram-inch). The dynamic balancing of the rotor was made on a Gisholt balancing machine. Final rotor assembly balance was made with the assembly containing the selected bearings and prebalanced cartridges. The balance machine was checked for sensitivity by placing 0.00035 kg (0.2 grams) on the three impellers alternately at 1.57 radian (90 degree) increments and checking the imbalance. The results indicated the variation in sensitivity to be 2.03×10^{-4} mm (8×10^{-6} inch). The final assembly runouts were measured and recorded in Fig. 27.

The rotor balance was checked as a function of various angular positions of the hydrostatic cartridges with the cartridges in static position. For a total of nine mixed orientation positions, the rotor balanced within 1.35×10^{-3} kg-mm (0.03 gram-inch) at the instrumentation nut and turbine wheel balance planes. Several attempts were made to set up a balance system whereby the cartridges could rotate with the rotor, but none were successful. This was due in part to the low friction torque of the assembled bearing which was measured at 022.6 N-mm (0.2 inch-pound) for an assembly preload of 578 N (130 pounds). The rotor balance was considered to be satisfactory. Satisfying the rotor balancing requirements must be considered as a priority problem with the incorporation of hybrid bearings into a high-speed turbopump.

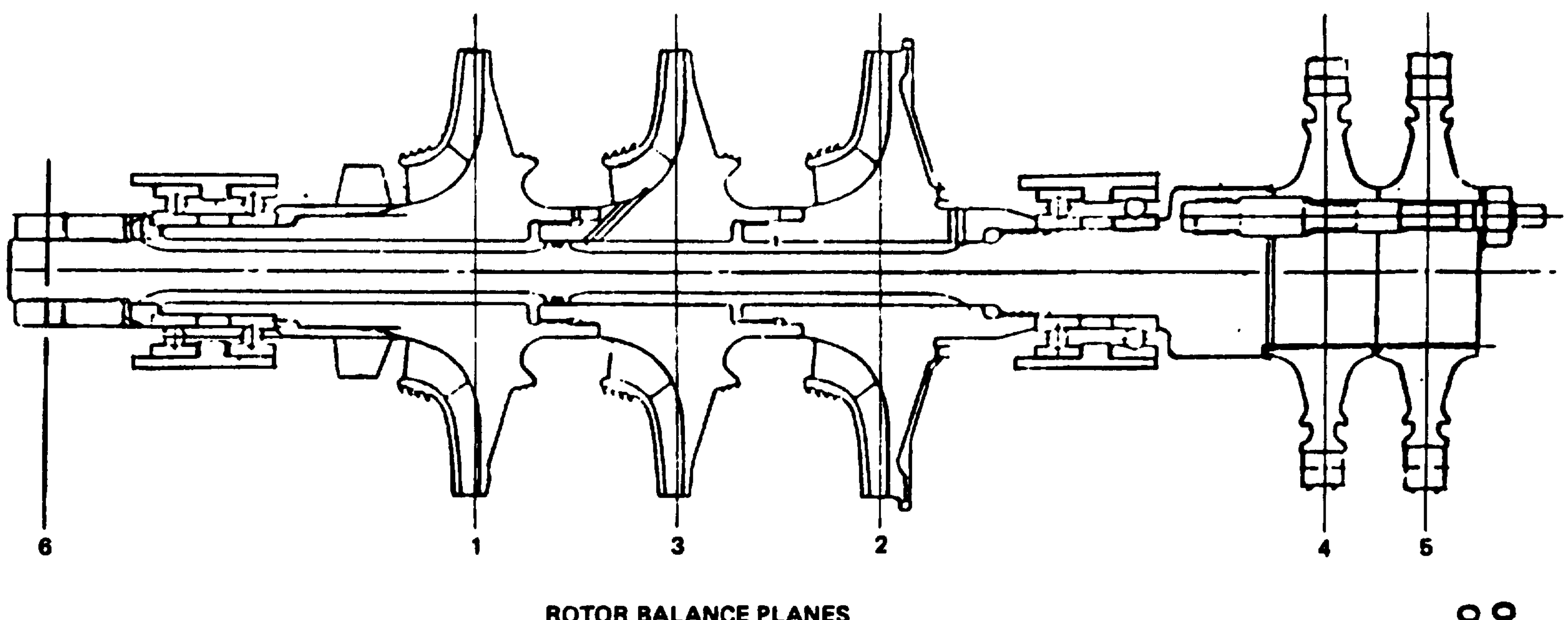


Figure 25. Mark 48-F Turbopump Rotor Balance Assembly

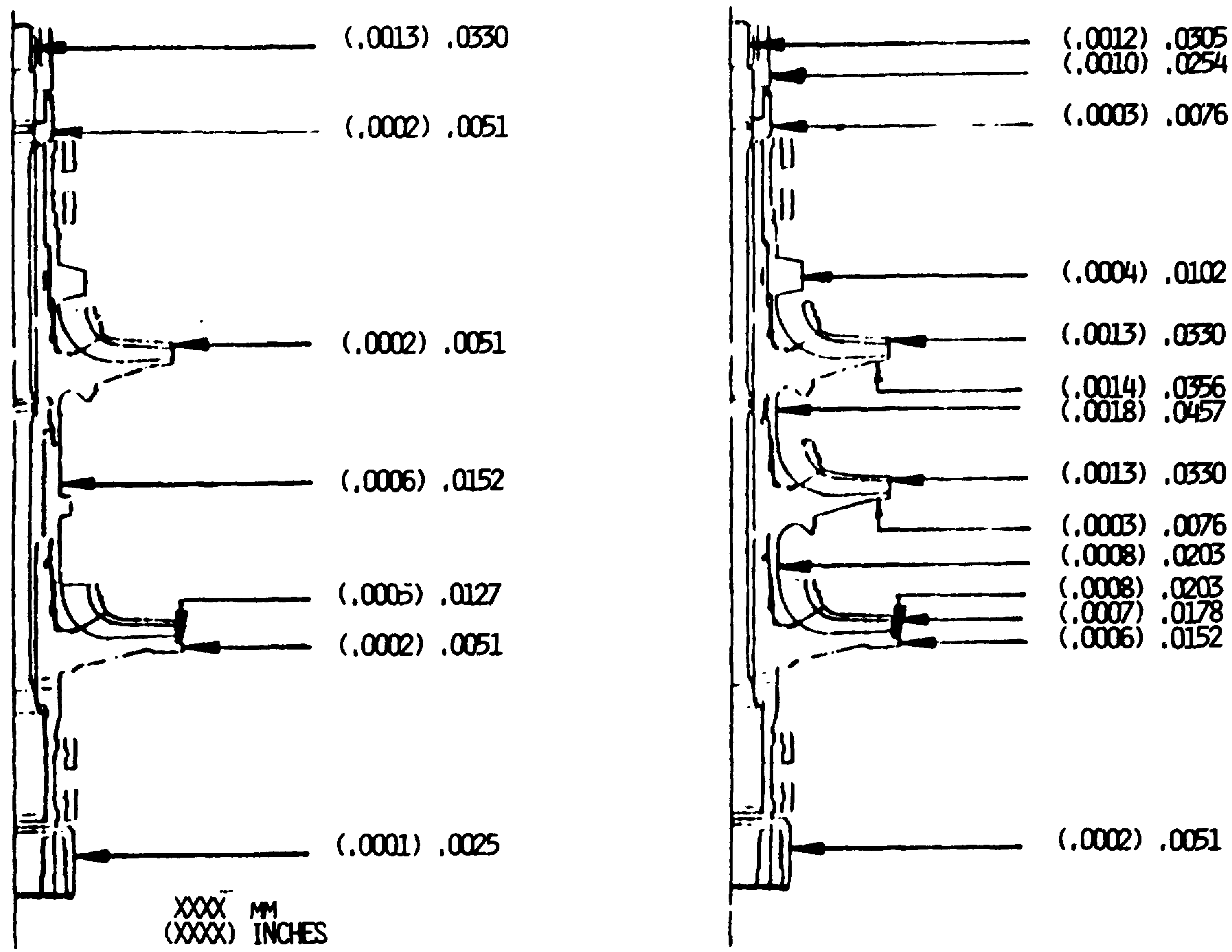


Figure 26. Partial Assembly Runouts During Balancing

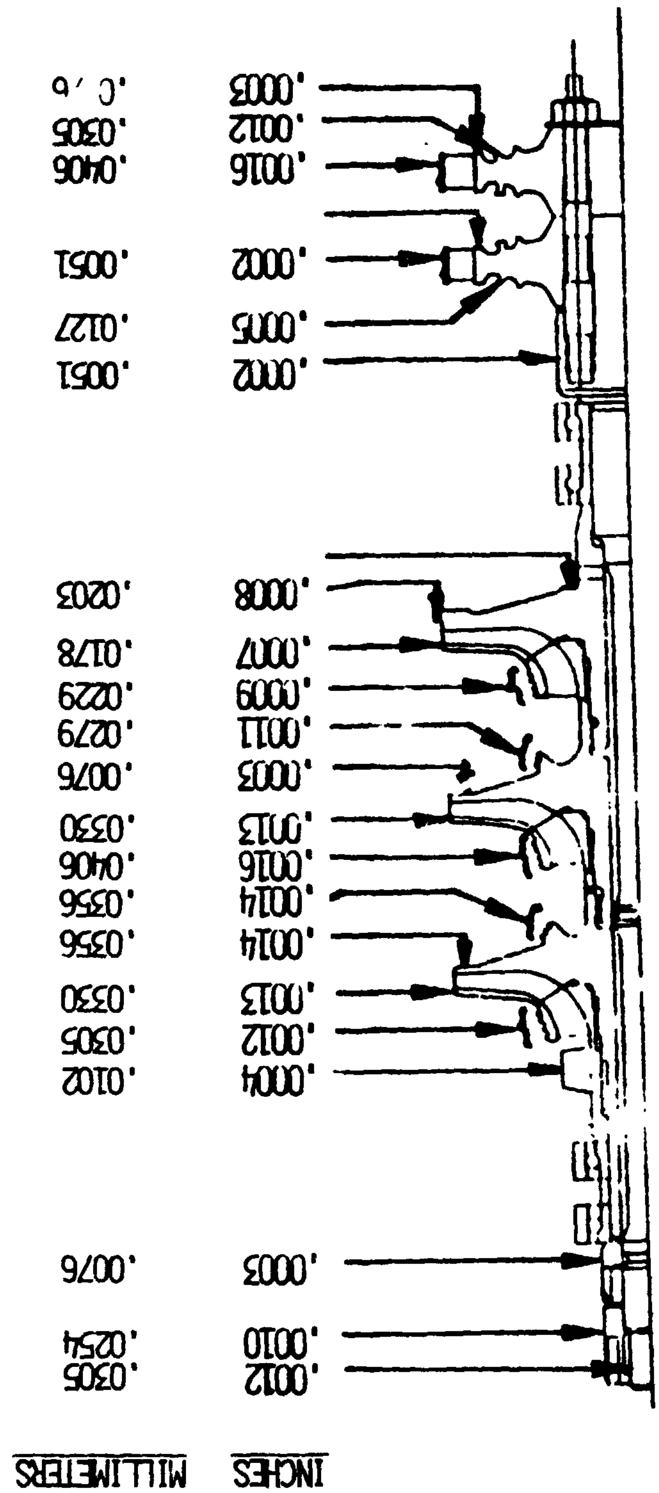


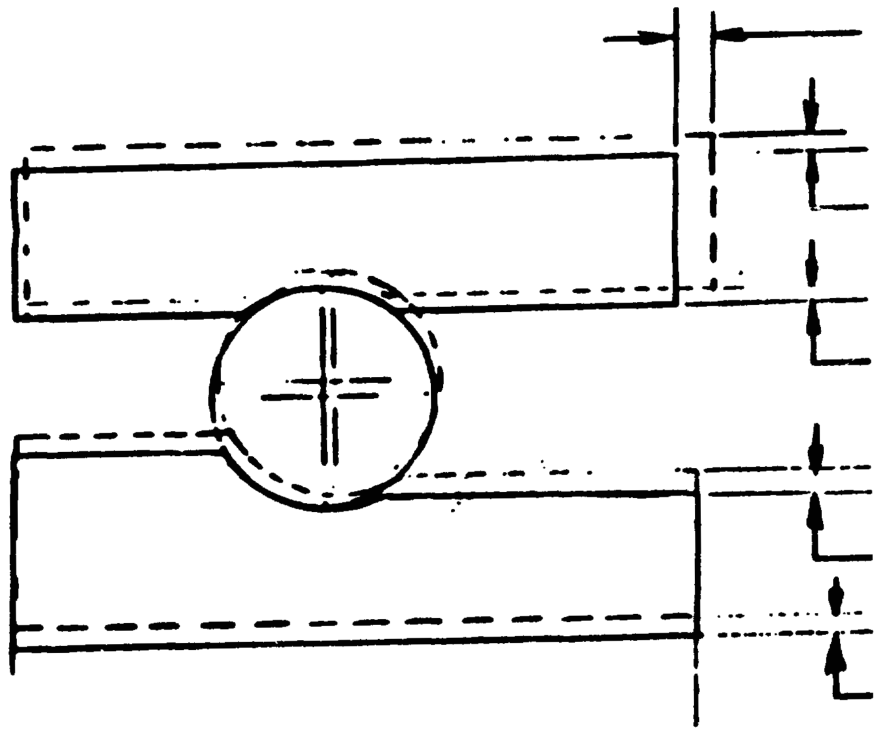
Figure 27. Mark 48-F Turbopump (S/N 02-1) Assembly Runouts

Assembly - Balance Piston Positioning

The axial positioning of the balance piston orifices to coincide with end play clearances of the turbine-end hydrostatic cartridge was recognized early in the program to be of major importance. If the clearances coincide properly, the balance piston is allowed to control shaft axial position while the hydrostatic journal is allowed adequate end play and, thus, is able to rotate freely. An additional concern, however, was the need to limit the axial travel of the shaft during start and shutdown thrust transients that the balance piston could not control. The need for this control resulted in a stackup analysis to determine the range of clearances required.

Due to the nature of the fine axial clearances required, a bearing stickout analysis was required to determine how the bearing axial position from inner to outer race changed with changes in outer and inner race rotation changes; this analysis is summarized in Fig. 28, which also shows the stickout changes due to the effects of preload and shrinkage due to temperature changes. The results of the study resulted in the balance piston position limits given in Fig. 29. Ambient static to chilled operating conditions were developed and are given in Table 3. In previous builds, the balance piston allowable travel between bearing stops was set at approximately 0.279 mm (0.011 inch). This is for the range of axial load exerted on the bearing stops (or bearings) of 1779 N (400 pounds) in each direction. It was found, however, that bearing spring compression and stickout changes accounted for approximately half of the axial shaft travel allowance and would allow only 0.152 mm (0.006 inch) total end play for the turbine-end hydrostatic bearing cartridge if allowable balance piston travel was held at 0.279 mm (0.011 inch). Analysis of hardware and data from previous builds indicated transient shaft axial thrust was toward the turbine and had caused the low-pressure rub ring some wear, whereas no evidence of high shaft thrust toward the pump end was seen. As a result, it was decided that a compromise would be used with the allowable travel on the balance piston being raised to approximately 0.373 mm (0.0147 inch), thus allowing the net chilled clearance or end play of the bearings to be 0.257 mm (0.0101 inch). In this arrangement, the low-pressure rub ring was to be protected from excessive rubbing in start transients, while the high-pressure orifice could have a negative clearance. The high-pressure orifice lip on the impeller diametrally clears the housing section of the orifice in ambient and chilled conditions. The effects of rotation, however, allow the diameter of the impeller tip to grow, thus causing the radial clearance of the orifice to become negative. Similarly, due to impeller and housing deflections, as speed and pressure increases, the balance piston travel gap increases from 0.137 mm (0.0054 inch) to 0.257 mm (0.0101 inch).

The data in Fig. 30 show the results of the final assembly push-pull test of the shaft in LN_2. This test is done to verify that the axial position stackup of the balance piston and thrust control bearing are correct. The results show that the turbine-end journal touches the aft rub ring ($G_2 = 0$) at a position 0.0533 mm (0.0021 inch) before the balance piston low-pressure rub ring makes contact. The figure also indicates the predicted positions of the high-pressure orifice $H_1 = 0$ for the conditions of ambient-static, chilled-static, and chilled-high speed-pressurized. The predicted steady-state shaft operating position range at



PARAMETER	Ni = 95,000 RPM No = 0 RPM		Ni = 95,000 RPM No = 95,000 RPM	
	INCHES	mm	INCHES	mm
Stickout Change	+.0005	.0127	-.00102	-.0259
Outer Race O.D.	0.0	0	.00167	.0424
Outer Race I.D.	0.0	0	.00176	.0447
Inner Race O.D.	.00230	.0584	.00230	.0584
Inner Race I.D.	.00230	.0584	.00230	.0584

CONCLUSION:

A. Inner Race only rotating at 9948 rad/sec (95,000 RPM).
Spring compression increases by ~0.0127mm (0.0005 inch) per bearing

B. Both races rotating at 9948 rad/sec (95,000 RPM).
Spring compression relaxes by ~0.0254 mm (0.0010 inch) per bearing

Figure 28. Bearing Fits and Stickout Changes

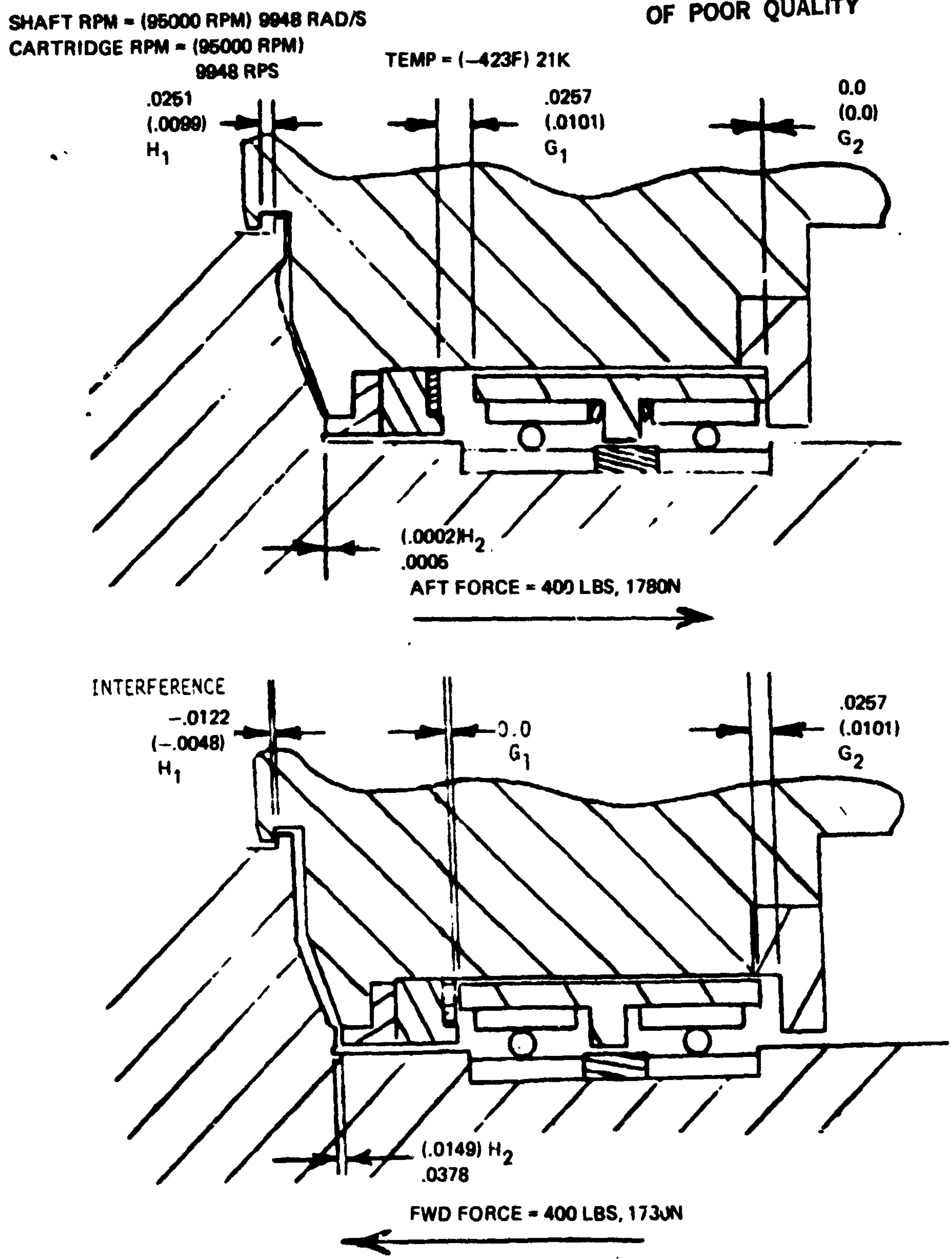


Figure 29. Turbine End Cartridge - Balance Piston System Axial Position Limits

TABLE 3. BALANCE PISTON - BEARING CARTRIDGE

POSITION SUMMARY (SEE FIGURE 29)
MARK 48F TURBOPUMP WITH HYBRID BEARINGS

T/P CONDITION

	SHAFT		CARTRIDGE		FORCE		H_2		H_1		G_2		G_1	
TEMPERATURE	RPM	RADS/SEC	RPM	RADS/SEC	POUNDS	NEWTONS	INCH	MM	INCH	MM	INCH	MM	INCH	MM
AMBIENT	0	0	0	0	0 400	0 1780	0.0017 0.0000	0.0432 0.0000	0.0029 0.0046	0.0737 0.1168	0 0	0 0	0.0098 0.0098	0.2489 0.2489
-423 F 20 K	0	0	0	0	0 400	0 1780	0.0034 0.0013	0.0864 0.0330	0.0012 0.0033	0.0305 0.0838	0 0	0 0	0.0101 0.0101	0.2565 0.2565
-423 F 20 K	95K	10K	95K	10K	0 400	0 1780	0.0027 0.0002	0.0686 0.0051	0.0075 0.0099	0.1905 0.2515	0 0	0 0	0.0101 0.0101	0.2565 0.2565
-423 F 20 K	95K	10K	0	0	0 400	0 1780	0.0026 0.0009	0.0660 0.0229	0.0075 0.0092	0.1905 0.2337	0 0	0 0	0.0101 0.0101	0.2565 0.2565
AMBIENT	0	0	0	0	0 -400	0 -1780	0.0112 0.0129	0.2845 0.3277	-0.0066 -0.0083	-0.1676 -0.2108	0.0098 0.0098	0.2489 0.2489	0 0	0 0
-423 F 20 K	0	0	0	0	0 -400	0 -1780	0.0121 0.0142	0.3073 0.3607	-0.0075 -0.0096	-0.1905 -0.2438	0.0101 0.0101	0.2565 0.2565	0 0	0 0
-423 F 20 K	95K	10K	95K	10K	0 -400	0 -1780	0.0125 0.0149	0.3175 0.3785	-0.0024 -0.0048	-0.0610 -0.1219	0.0101 0.0101	0.2565 0.2565	0 0	0 0
-423 F 20 K	95K	10K	0	0	0 -400	0 -1780	0.0126 0.0143	0.3200 0.3632	-0.0025 -0.0042	-0.0635 -0.1067	0.0101 0.0101	0.2565 0.2560	0 0	0 0

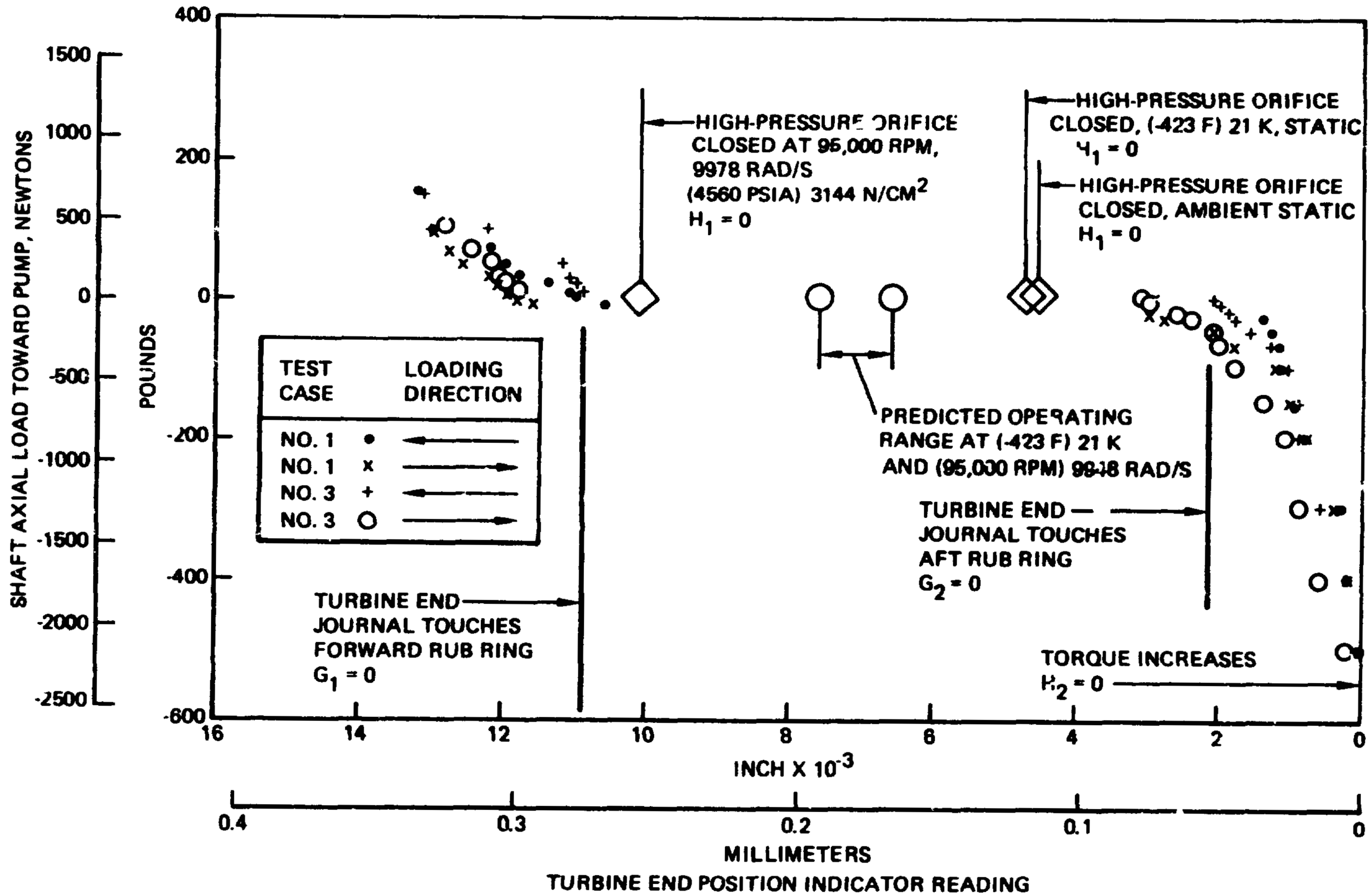


Figure 30. Final Assembly Push-Pull Test in Liquid Nitrogen

9948 rad/sec (95,000 rpm) is given as between H_2 = 1.676 mm (0.066 inch) and 1.930 mm (0.076 inch). The position is only slightly biased toward the high-pressure orifice but indicates sufficient capacity and gap for proper operation.

The exercise of trying to obtain hydrostatic journal bearing axial end-play in a turbopump with a balance piston thrust control is inherent in the design of hydrostatic bearings in a high-pressure turbopump. Hydrostatic bearings require free end-play for allowing the cartridge to rotate with the shaft. Similarly a "floating" shaft requires a high tolerance balance piston for efficient operation which operates effectively at high speeds. For these designs then, the start and cutoff transients require high tolerance shaft position control devices which may or may not be independent of the hydrostatic bearings. It is clearly evident by these studies that the hydrostatic bearing design considerations for high-speed turbopumps must include detailed development of shaft position control.

Assembly - General

The assembly of the turbopump was very closely controlled with critical clearances and build dimensions monitored throughout the build. The verification of clearances was generally taken by diameter or depth gage measurements of major components during assembly. Clearances on the pump inlet components are given in Fig. 31 including the radial and axial clearances of the position transducers. Impeller-inducer pilot diametral clearances are shown in Fig. 32. The impeller seal labyrinth diameters were measured on each labyrinth and the resultant diametral clearances are given in Fig. 33. The turbine-end bearing and turbine seal clearances are given in Fig. 34. Note the press fits required on the bearing inner races to shaft diameters. These dimensions were used in the bearing stick-out analysis for balance piston-turbine-end bearing spacing. The proximeter minimum radial gap for the cartridge speed monitoring also is shown. The diametral clearances for the turbine seals are shown in Fig. 35. The small clearances indicated at the turbine tip are from the tip of the seal rings to the copper-plated inside diameter of the seal rings. Similar clearances have been run to high speeds in other ambient GH_2 drive tests on this turbopump without excessive seal wear or rubbing problems. Figure 36 presents the turbine blading axial clearances of the test build. The nozzle-to-blade clearances were set in conformance to required spacing dictated by aerodynamic design principles.

Upon completion of the assembly including instrumentation installation, a leak check was made to verify the assembly was sealed properly. Several minor leaks were found and corrected. After leak checks, the pump end of the turbopump assembly was insulated by polyurethane foam covered with a fiberglass shell. The turbopump was then installed in the test base. The completed turbopump assembly, insulated and installed in its base, is shown in Fig. 37. With the completion of the assembly, the turbopump was transported to the Advanced Propulsion Test Facility (APTF) at the Rocketdyne Santa Susana test facility (SSFL) for installation and test.

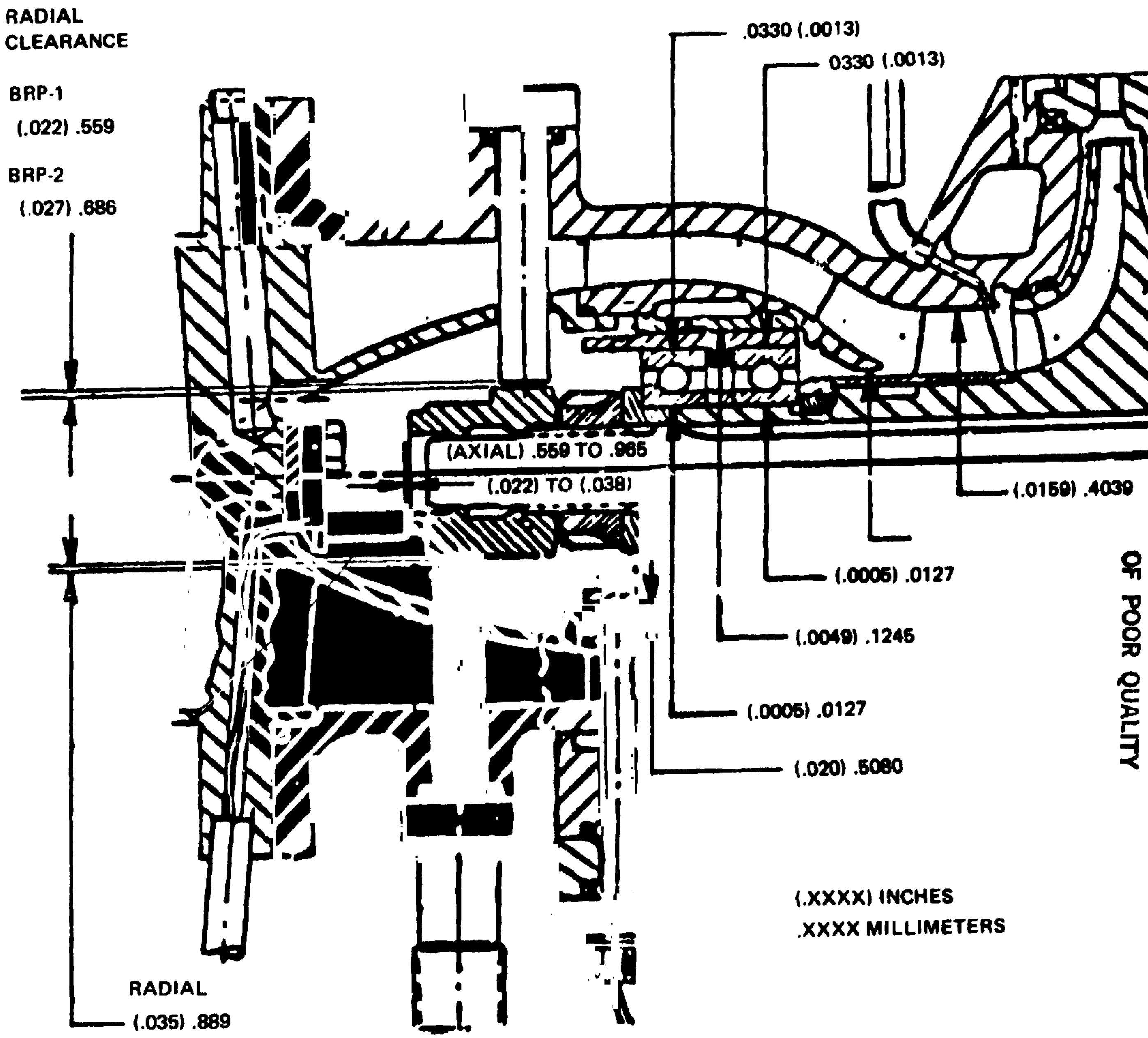


Figure 31. Mark 48-F Diametral Clearances - Pump Inlet Components

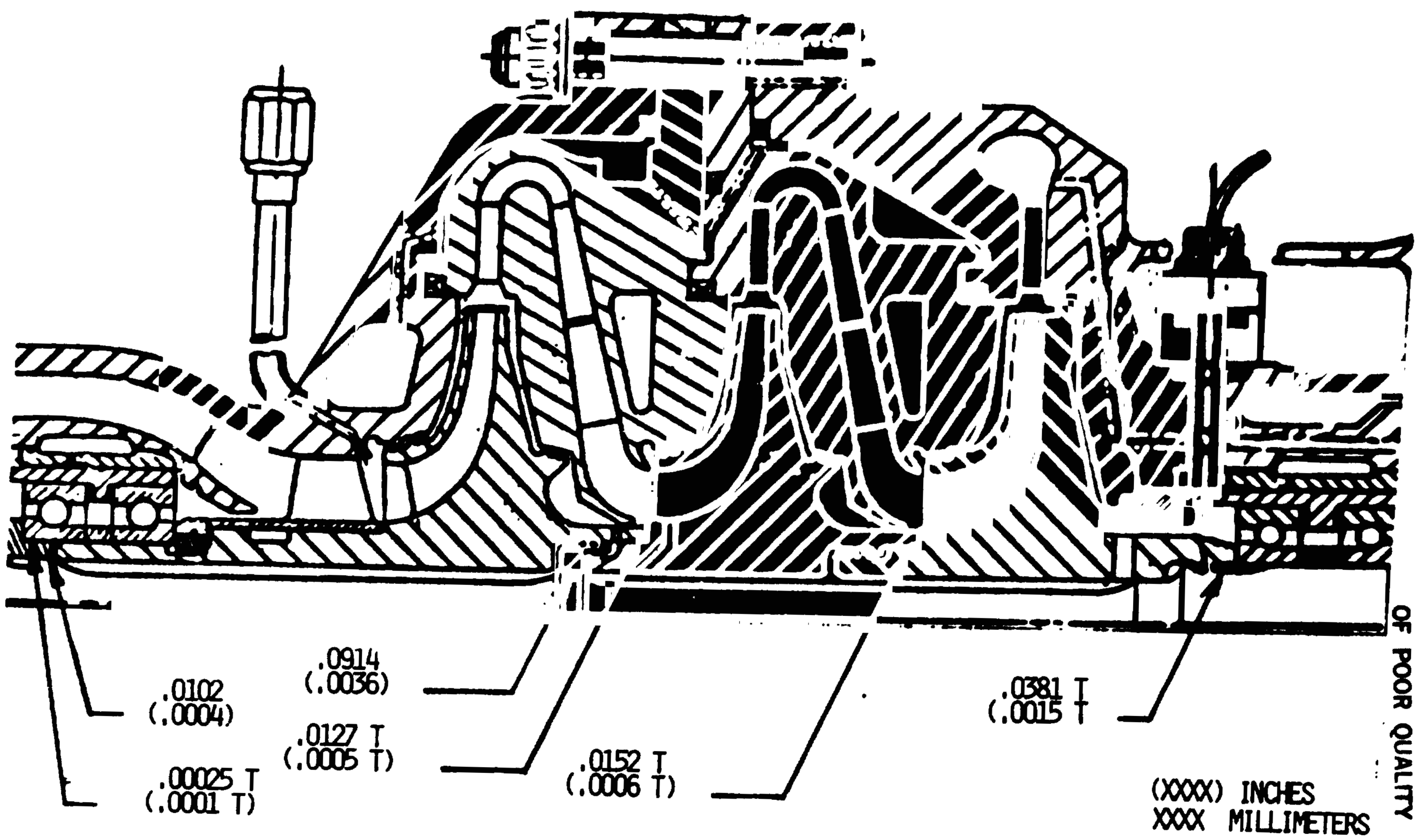


Figure 32. Mark 48-F Impeller-Inducer Pilot Diametral Fits

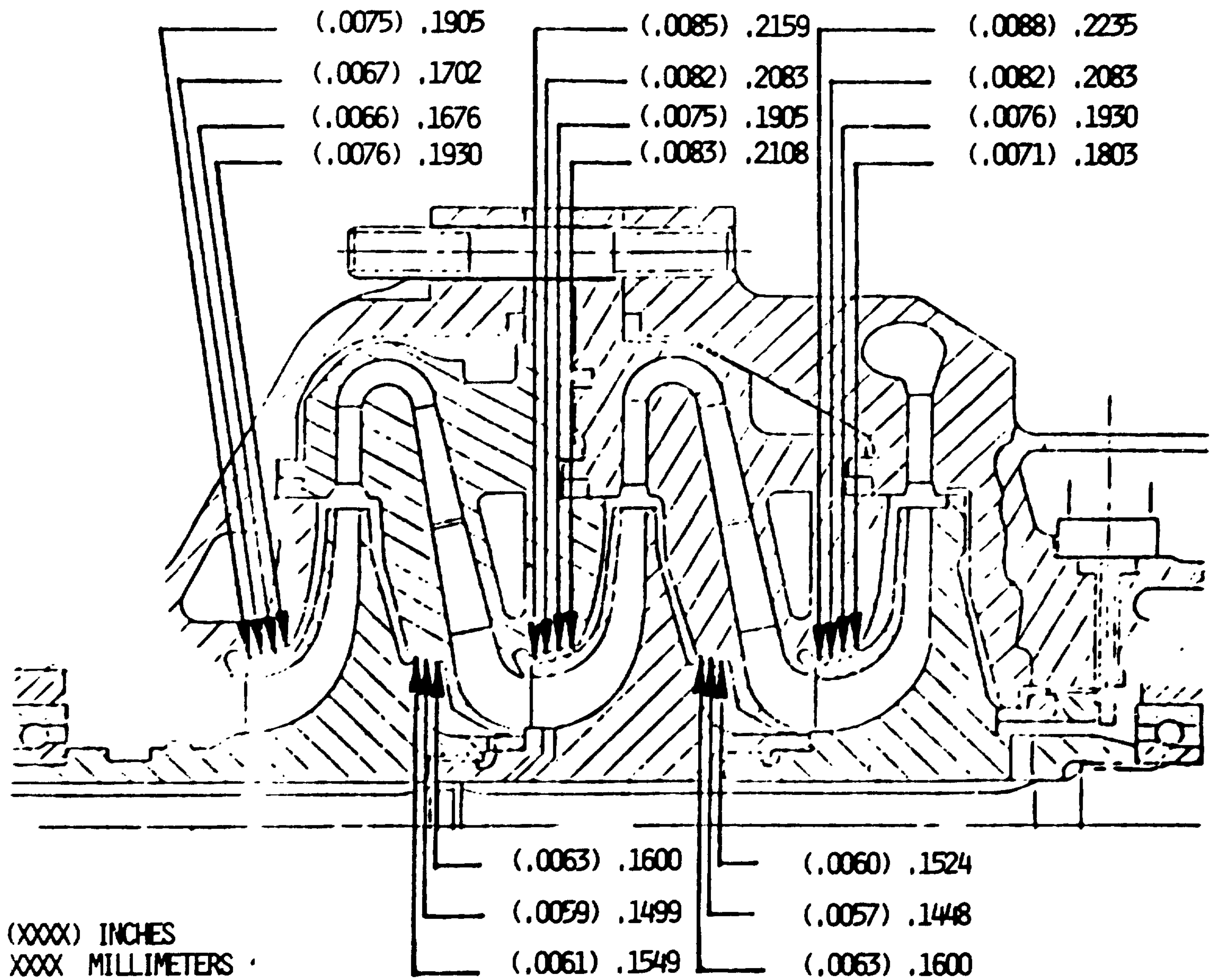


Figure 33. Mark 48-F Turbopump (S/N 02-1) Impeller Labyrinth Diametral Clearances

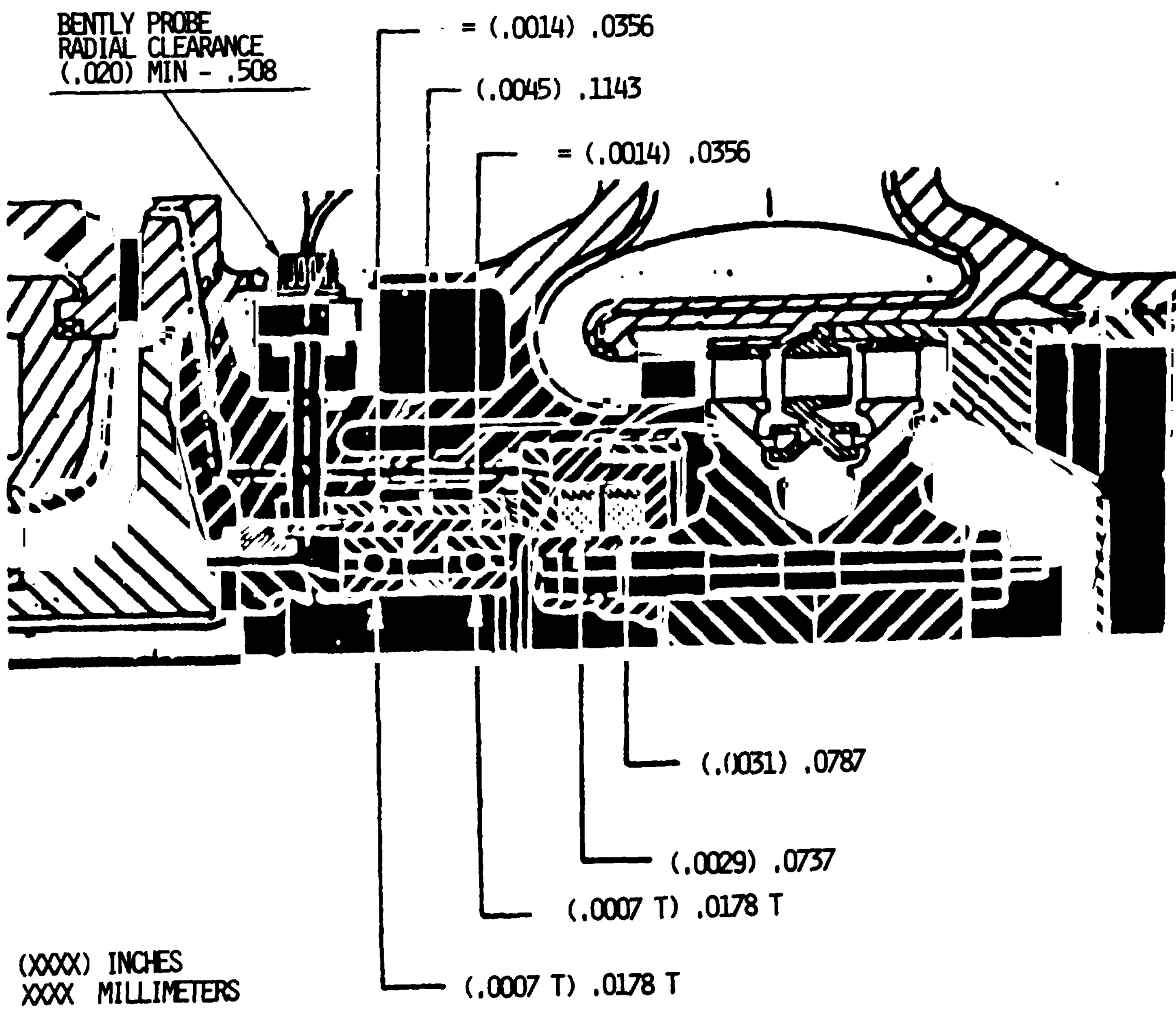


Figure 34. Mark 48-F Turbine-End Bearing and Seal Diametral Clearance and Fits

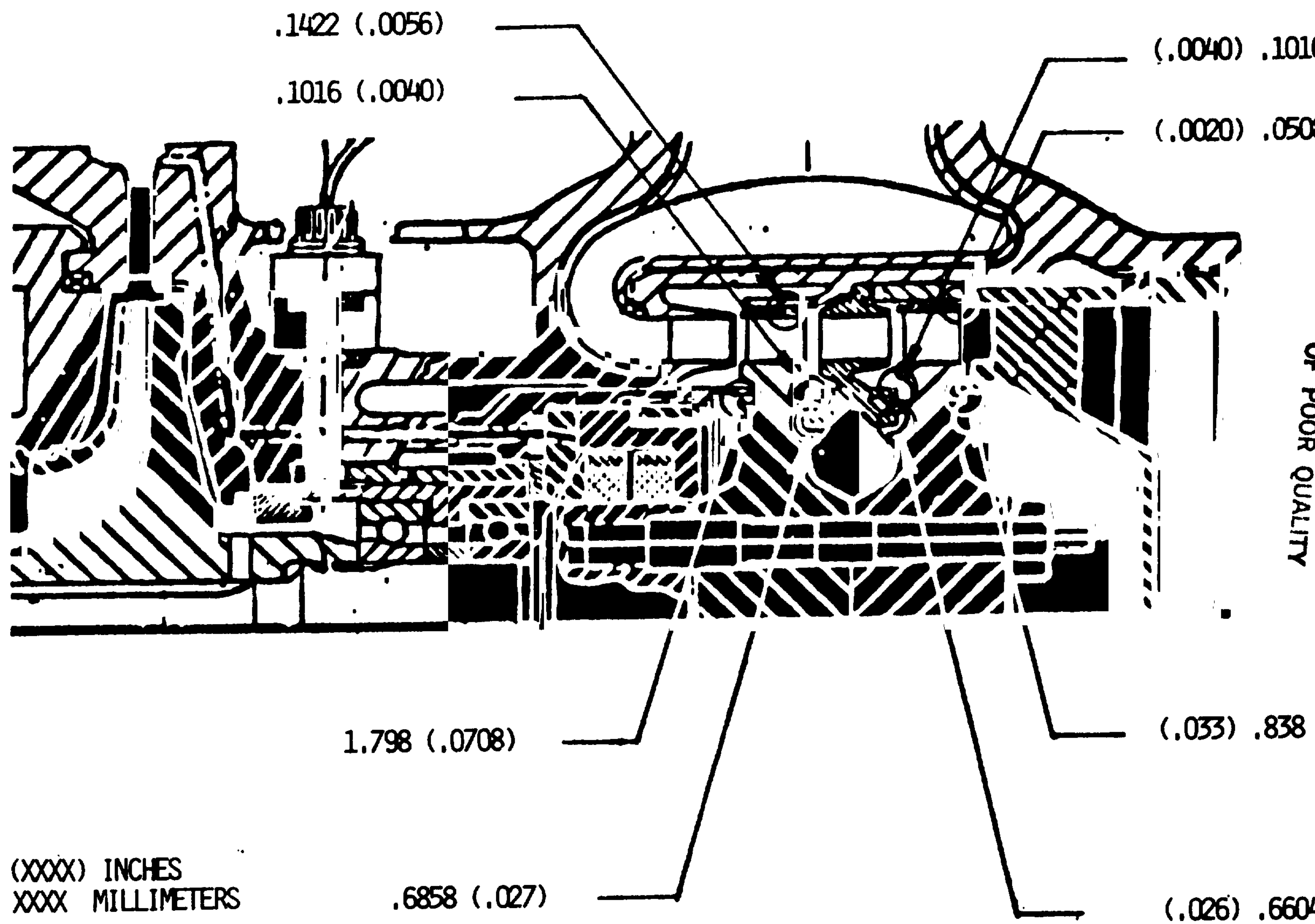


Figure 35. Mark 48-F Turbine Seal Diametral Clearances

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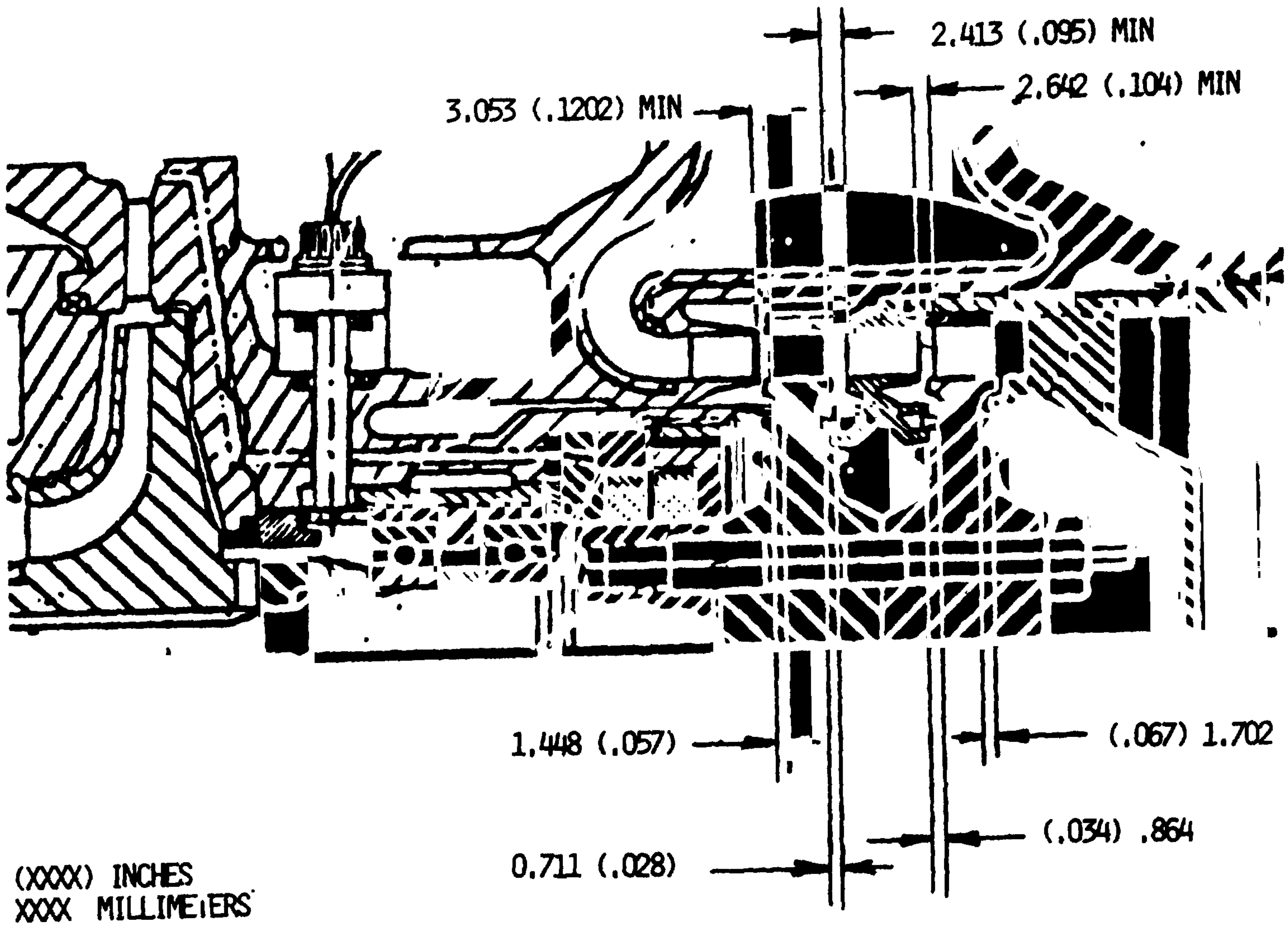

Figure 36. Mark 48-F Turbine Blading Axial Clearances

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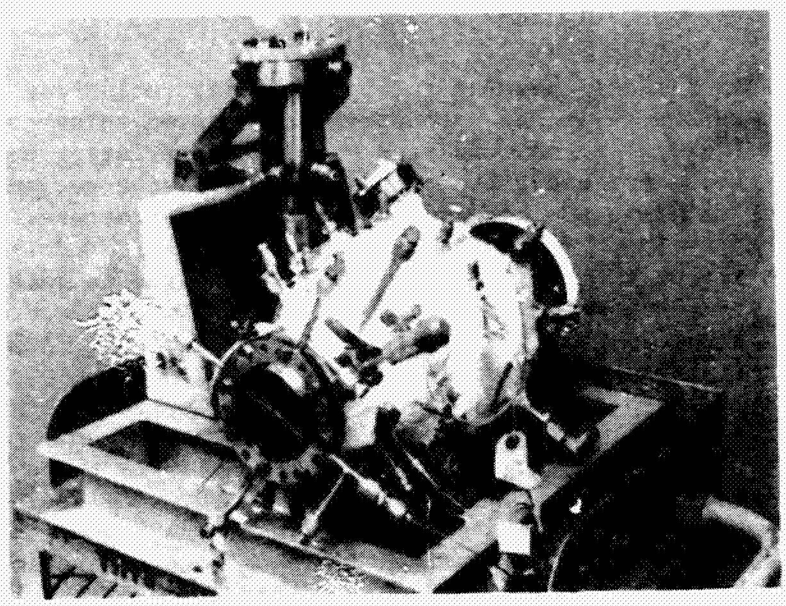

Figure 37. Assembled Turbopump

TESTING

Installation

The hybrid, hydrostatic/ball bearing turbopump configuration was installed in APTF Lima test stand where it had been previously tested using conventional ball bearings. Initial installation consisted of plumbing existing ducting to the main turbopump interfaces, e.g., the pump inlet and discharge, and turbine inlet and discharge and securing the base to the test stand structure.

During turbopump assembly, the test facility was prepared to receive the turbopump for test. The basic major ducting requirements and tankage to be used for the turbopump is shown in the facility schematic of Fig. 38. A major requirement for these tests was to provide a closely controlled supply of high-pressure liquid hydrogen for the hydrostatic bearings from a source external to the turbopump. This hydrogen supply also had to be controlled so that the pressure of the supply in the hydrostatic bearing manifold could duplicate the pressure levels supplied by the turbopump as a function of pump speed. The design of two controllers, one for each of the hydrostatic bearings, was begun early in the test preparations and installed in the facility. These controllers were designed to provide a hydrostatic bearing manifold supply pressure as a function of pump pressure levels fed back to the controller. The impeller first-stage discharge pressure was the feedback pressure reference for the pump-end bearings and the pump discharge pressure was used as the feedback reference pressure for the turbine-end bearings. The controllers can be independently used to provide the respective feedback pressures to the hydrostatic bearing manifold. They also can be set to provide a positive bias (value greater than reference pressure by a constant) and also provide a limit to the pressure level (for maximum supply pressures allowed by structural limitations). The controller designs effectively provided the pressure levels required within the limits of the external supply pressure source.

The pump-end and turbine-end hydrostatic bearing supply system is depicted schematically in Fig. 39 and 40, respectively. Also shown is some of the turbopump instrumentation. The fluid supplied for each system goes through the controller regulator. Downstream of the controller is the sharp-edged orifice flow measuring device for measuring pressure drop across an orifice and temperature instrumentation before the fluid enters the turbopump bearings. The pump-end bearing drain line is shown in Fig. 39. In Fig. 40, the turbine-end supplemental drain line is shown. This drain was used and dumped overboard, although the majority of the balance piston sump flow goes back to the second-stage impeller inlet.

The placement of the turbopump in the facility was completed by installation of the instrumentation lines (Fig. 41 and 42). The large number of facility and turbopump instrumentation lines for the pressure measurements were plumbed individually from each pressure tap source to banks of pressure transducers located on the top, bottom, and sides of the turbopump stand. The electrical wiring from the transducers was routed to the facility recording center. Temperature and Bently proximeter signal cables were similarly routed. In Fig. 41, the servocontroller mechanism for the pump-end and turbine-end bearings is shown on the left

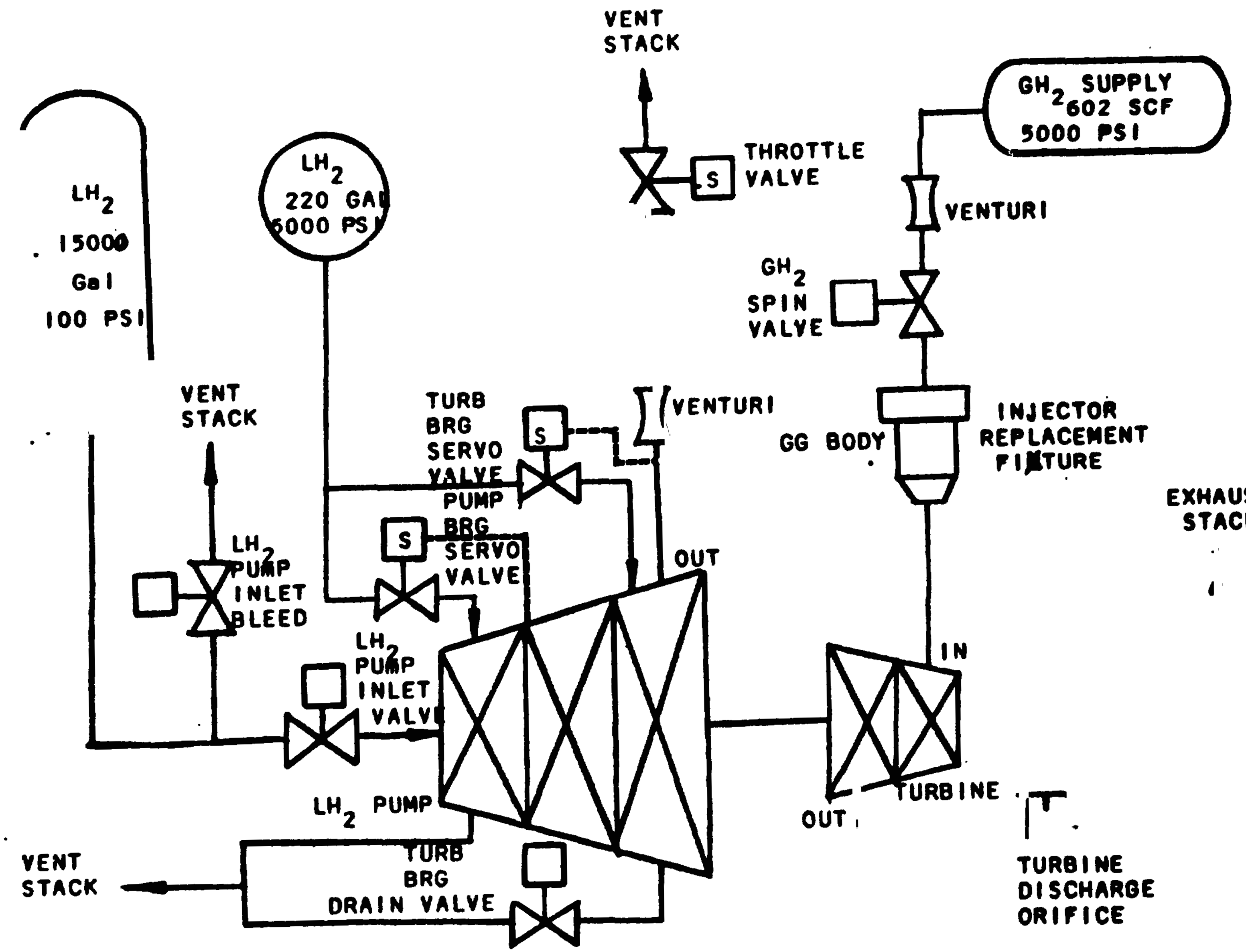

Figure 38. Gaseous Hydrogen Turbine Drive and Hydrostatic Bearing External Supply

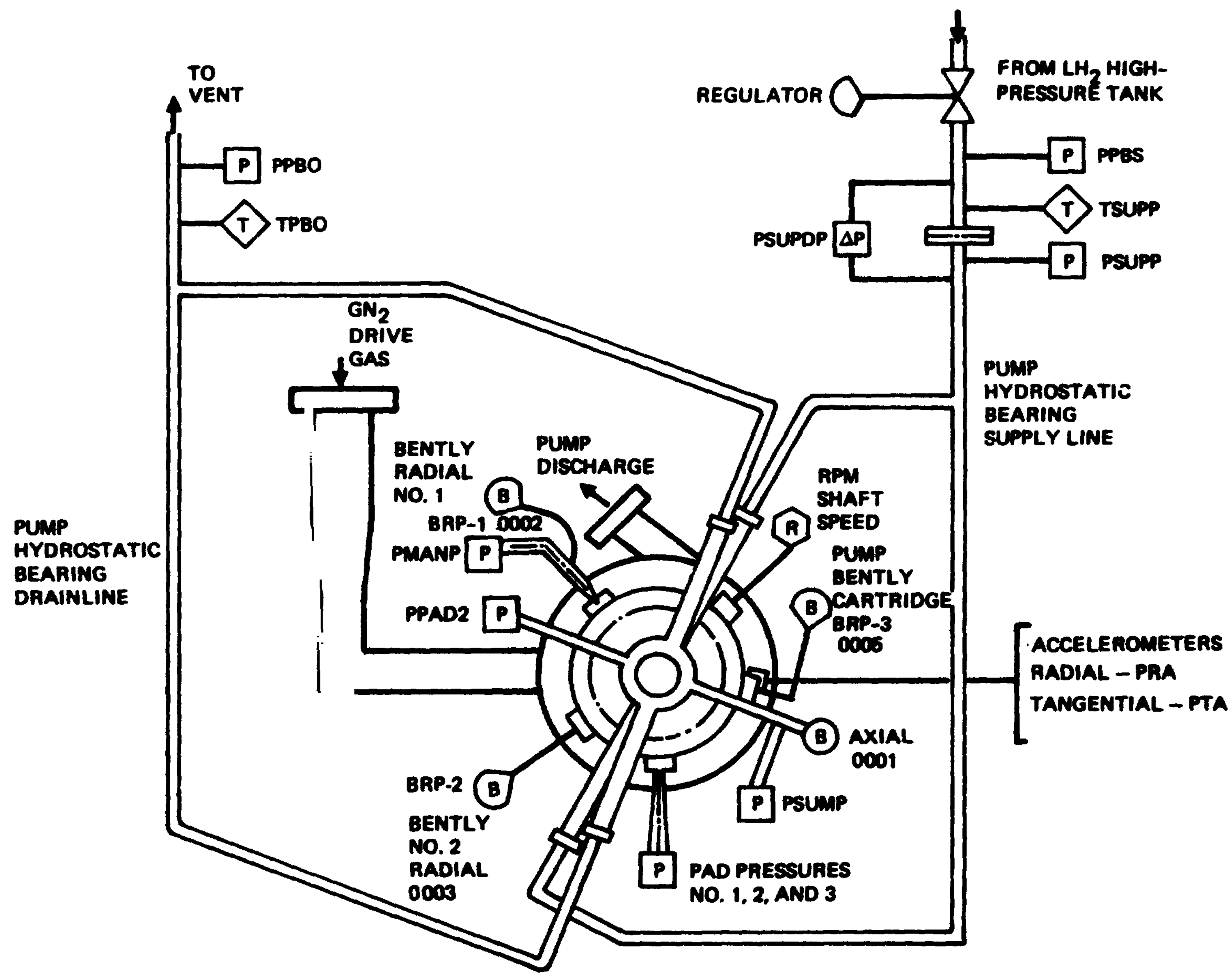

Figure 39. Pump-End Hydrostatic Bearing Supply System and Instrumentation

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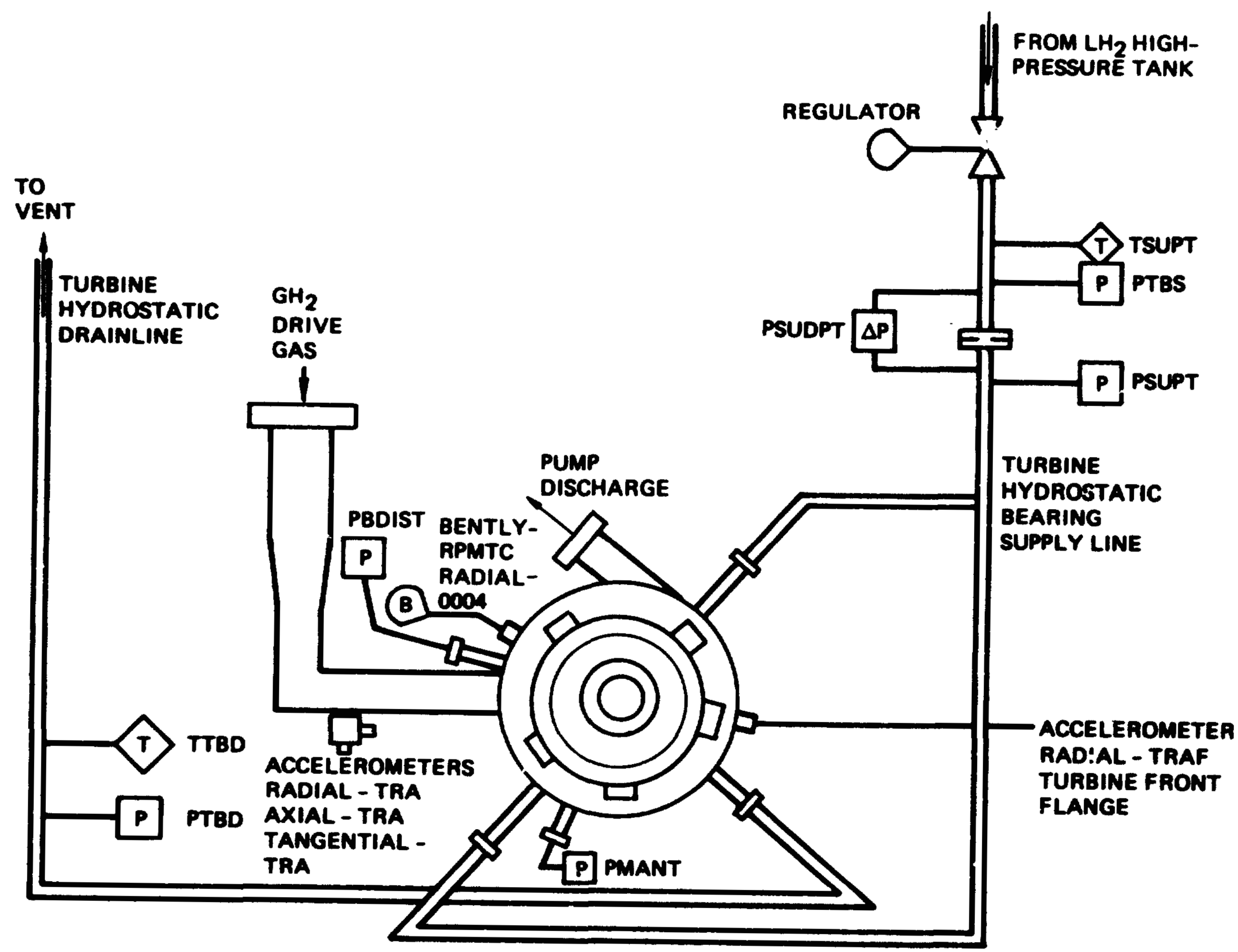

Figure 40. Turbine-End Hydrostatic Bearing Supply System and Instrumentation

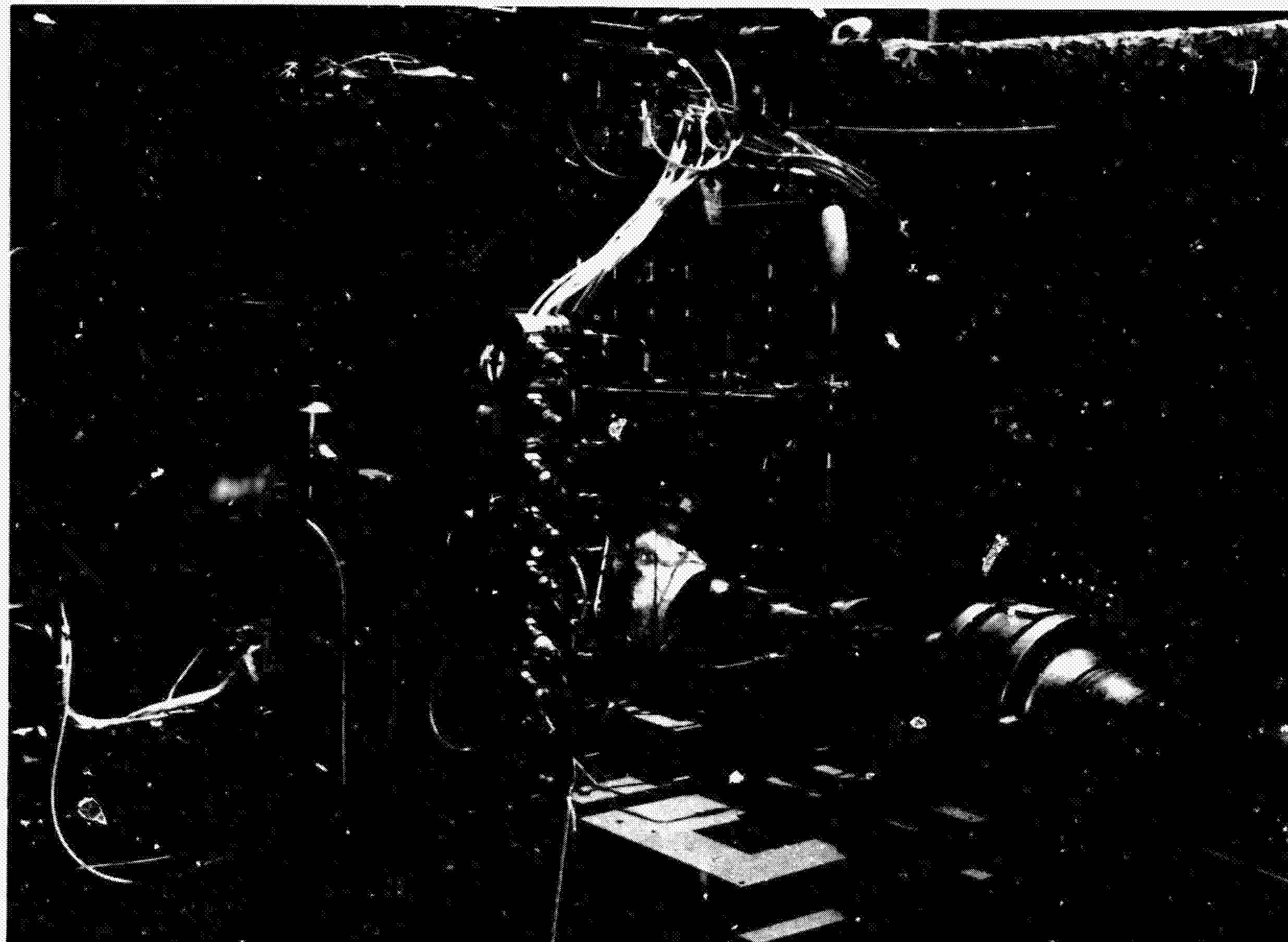

Figure 41. Mark 48-F Turbopump Installed - Turbine Exhaust Side

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Figure 42. Turbopump Installation - Pump Inlet Side

and right side of the turbopump, respectively. The photographs were taken prior to the insulation of all the liquid hydrogen supply and pump flow lines. Figure 42 shows the pump inlet side of the installation. For this configuration, the external bearing supply was in use. The pump internal hydrogen supply to the hydrostatic bearings was not plumbed in, resulting in eight blanked lines extending from the pump first-stage impeller area of the housing and a plugged tapoff in the pump discharge line just downstream of the piezometer ring and pump discharge temperature ports (upper left section of Fig. 42).

Instrumentation

The instrumentation conformed to turbopump and facility requirements to monitor the turbopump and control the tests. These requirements were reviewed and defined in the test plan approved by the NASA-LeRC project manager (Ref. 17). The instrumentation for the turbopump is given in Fig. 43. The turbopump body and internal sections were heavily instrumented with pressure, temperature, Bently proximeter, magnetic speed, and accelerometer sensors. Other sensors monitored all facility ducting and tankage.

All pressure, temperature, and flow measurements were recorded on tape during each test by means of a Beckman Model 210 Data Acquisition and Recording System. This system acquires data from the transducers and converts the data to digital form in binary-coded decimal format. The latter is recorded on tapes which are then used for computer processing. The Beckman Data Acquisition Unit sequentially samples the input channels at a rate of 5625 samples per second. Programmed computer output consists of tables of time versus the average parameter value over a preselected slice time printed out at the appropriate slice time intervals for the run duration. Calibration factors, prerun and postrun zero readings, and related data also are provided. The instantaneous parameter values are machine-plotted and displayed as CRT outputs on appropriately scaled and labeled grids for simple determination of gradients, establishment of steady-state conditions, etc. For the turbopump tests, a computer program was available to calculate propellant flowrates and turbopump actual and scaled performance parameters. This program was modified to include hybrid bearing parameters from its previous use on conventional ball bearing testing of this turbopump.

The primary data recording system for the testing was the Beckman 210 System. The following auxiliary recording systems also were employed:

1. One Honeywell direct reading oscillograph was used to record the dynamic data such as Bently shaft movement, accelerometer data, and raw shaft speed signal.
2. Direct-inking graphic recorders (DIGRs); three six-channel Watanabe strip chart recorders and nine Esterline-Angus two-channel strip chart, recorders were used. These charts aided in setting prerun propellant supply pressures and, also, were used for recording of system temperatures and pressures to provide quick-look information and redline monitoring, and as secondary backup to the Beckman and oscillograph recorders.

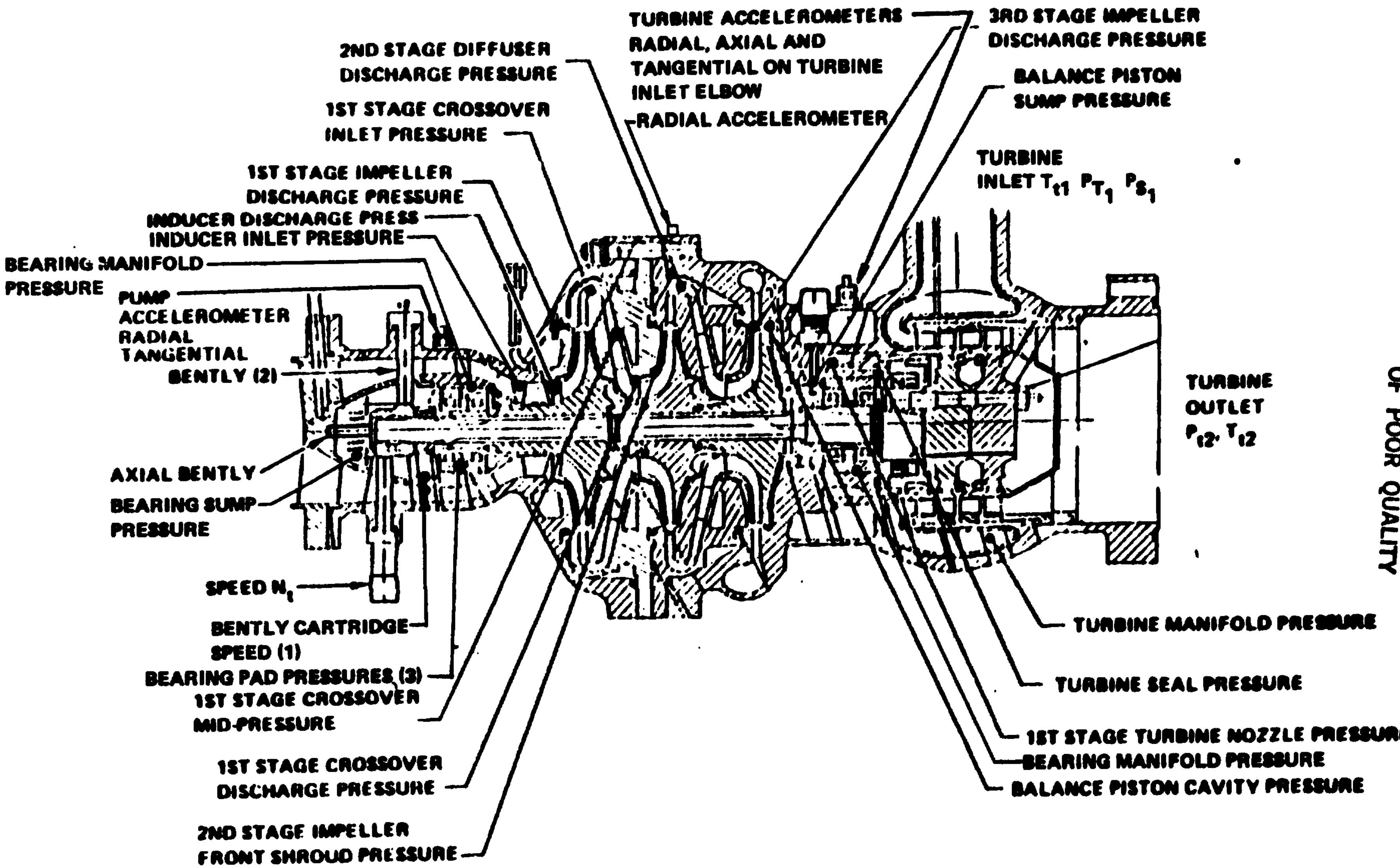

Figure 43. Mark 48-F Turbopump Instrumentation

3. Event recorders to record sequences and other event functions

4. A high-frequency tape recorder was used to record output of high-frequency transducers, including proximeters, accelerometers, and speed signals. A real time and test start signal was included for data analysis.

5. Oscilloscopes were used for real time display of the Bently transducer and accelerometer outputs to be used as redlines during operation if certain anomalies occurred.

6. A television camera was utilized with taped replay capabilities. Key areas of the turbopump system were monitored for real time operational analysis.

7. Bell and Howell motion picture coverage was required for each test. Film processing was determined following each test. No film processing was required.

8. Still photographs of each test hardware installation were required for presentation in test reports.

A summary of all the instrumentation requirements for the turbopump test program is shown in Table 4. They include instrumentation to obtain the basic performance data of the pump and turbine, facility instrumentation to control the test, and special instrumentation for operation of the hydrostatic bearing flow systems on both pump and turbine sides. The table utilizes the same parameter identification on those parameters used in previous testing and indicates the type of instrumentation required.

Instrumentation and transducer calibrations were used to obtain appropriate factors for test data reduction and to develop statistical histories for each transducer so that estimates of short- and long-term deviations could be made and probable error bands calculated. The calibration methods used for the various types of transducers are described below.

Pressure transducers are calibrated against high-precision Bourdon tube gages. The latter are calibrated periodically on Ruske deadweight testers, with weights traceable to NBS.

Subsonic venturis are calibrated by the vendor for discharge coefficients as a function of Reynolds number with traceability to the National Bureau of Standards. Using the upstream pressure, upstream temperature, and upstream to throat differential pressure measurements, the flowrates are accurately calculated using a computer program that accounts for changes in density through the venturi and venturi dimensions due to the cryogenic temperatures. On small supply and drain lines, the flow was measured using sharp-edged orifices with measured pressure differences and temperatures used to calculate flow from the standard orifice equations.

Resistance of the platinum resistance thermocouples used in the propellant lines are converted to millivolt outputs by a triple-bridge system. Transducers are

TABLE 4. INSTRUMENTATION LIST - HYBRID BEARING TESTS

SYSTEM	PARAMETER	ID	PID	RANGE	REDLINE	BECKMAN	DIGR	OSC	FM TAPE	LOCATION
PUMP-INLET FLANGE										
	PMP HS BRG SUMP P	PSUMP		500 PSIG		X	X			T/P
	PMP HS BRG PAD 1 P	PPAD 1		2000 PSIG		X				T/P
	PMP HS BRG PAD 2 P	PPAD 2		2000 PSIG		X				T/P
	AXIAL SHFT BENTLY-0001	BAXS		0.025 IN.		X		X	X	T/P
	PMP HS BRG SUMP OUT P	PPBO		200 PSIG		X				FAC
	PMP HS BRG SUMP OUT T	TPBO		0 TO 150 R	X	X	X			FAC
	PMP HS BRG PAD 3 P	PPAD 3		2000 PSIG		X				T/P
PUMP-INLET HOUSING										
	PMP HS BRG MANIF P	PMANP		3000 PSIG		X	X			T/P
	INDUCER INLET P	P11	109	200 PSIG		X	X			T/P
	INDUCER DISCH P	P10	107	250 PSIG		X	X			T/P
	1 STG IMP DIS[illegible]	P11	091	2000 PSIG		X	X			T/P
	BENTLY RAD 3 [illegible]G-0005	BRP-3		100,000 RPM, 0.050 IN.	X	X	X	X	X	T/P
	PUMP SPEED	RPM	083	120,000	X	X	X	X	X	T/P
	BENTLY RAD 1 SHFT-0002	BRP-1		0.010 IN.	X			X	X	T/P
	BENTLY RAD 2 SHFT-0003	BRP-2		0.010 IN.	X			X	X	T/P
	PUMP RAD ACCEL	PRA		LOW PASS 2000 Hz AT 30 g, 5 TO 10 kHz AT 150 g	X			X	X	

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TABLE 4. (Continued)

SYSTEM	PARAMETER	ID	PID	RANGE	REDLINE	BECKMAN	DIGR	OSC	FM TAPE	LOCATION
PUMP INLET HOUSING - CONT'D										
	PUMP TANK ACCEL	PTA		5 TO 10 kHz at 150 g				X	X	T/P
	XOVER FLANGE PR	PCOB	059	1000 PSIG		X				T/P
	PMP HS SUP ORIF DP	PSUDPP		250 PSIG		X	X			FAC
	PMP HS BRG SUPPLY T	TSUPP		25 TO 300 R		X	X			FAC
	PMP HS BRG SUPPLY P	PPBS		3000 PSIG		X				FAC
	PMP BRG SUPPLY P	PPBS		3000 PSIG		X				FAC
FIRST-STAGE CROSSOVER										
	1 STG XOVR IN P	P12	092	2000 PSIG		X				T/P
	1 STG XOVR MID P	P13	093	2000 PSIG		X				T/P
	1 STG XOVR DISCH P	P14	081	2000 PSIG		X				T/P
	1 STG IMP FR SH P	P21	094	5000 PSIG		X				T/P
SECOND-STAGE CROSSOVER										
	2 STG DIFF DISCH P	P22	095	5000 PSIG		X	X			T/P
TURBINE HOUSING										
	T HS BRG MANIF P	PMANT		5000 PSIG		X	X			T/P
	T HS BRG DISCH P	PBDIST		3000 PSIG		X				T/P
	T HS BRG SUPPLY T	TSUPT	035	25 TO 300 R	X	X	X			FAC
	T HS BRG SUPPLY P	PSUPT		5000 PSIG	X	X				FAC
	TURB BRG SUPPLY P	PTBS		5000 PSIG		X				FAC
	TURB BRG DRAIN P	PTBD		1000 PSIG		X				FAC

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TABLE 4. (Continued)

SYSTEM	PARAMETER	ID	PID	RANGE	REDLINE	BECKMAN	DIGR	OSC	FM TAPE	LOCATION
TURBINE HOUSING - CON'T										
	TURB BRG DRAIN T	TTBD		25 TO 500 R	X	X	X			FAC
	T HS SUP ORIF DP	PSUDPT		250 PSID		X	X			FAC
	3 STG IMP DISCH P	P31	084	5000 PSIG		X	X			T/P
	BAL PIST CAV P	P41	096	5000 PSIG	X	X	X			T/P
	BAL PIST SUMP P	P42	086	5000 PSIG	X	X	X			T/P
	TURBINE SEAL P	PTS	076	5000 PSIG		X	X			T/P
	1 STG NOZZLE P	PT1	077	5000 PSIG		X	X			T/P
	TURBINE MANIF P	PTM	067	5000 PSIG		X				T/P
	TURBINE RAD ACCEL	TRA		5 TO 10 kHz AT 150 g				X	X	T/P
	TURBINE TANG ACCEL	TTA						X	X	T/P
	TURBINE AXIAL ACCEL	TAA						X	X	T/P
	BENTLY T HS BRG -0004 SPEED	RPMTC		100,000 RPM	X	X	X	X	X	T/P
	TURBINE FRONT FLANGE ACCEL RADIAL	TRAF		5 TO 10 kHz AT 150 g				X	X	T/P
PUMP PARAMETERS EXTERNAL										
	LH_2 P/V TEMP(HIGH PRESS)	LHPVT	041	25 TO 500 R	X	X				FAC
	LH_2 PUMP IN T2	THIN 2	043	25 TO 400 R	X	X	X			FAC
	LH_2 PUMP IN RUNLINE T	THRL	044	25 TO 400 R		X	X			FAC
	LH_2 PUMP DISCH T1	TPDT1	045	25 TO 400 R		X	X			FAC
	LH_2 PUMP DISCH T2	TUVP	046	25 TO 400 R		X	X			FAC
	T/V POSITION	TVP	057			X	X			FAC

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TABLE 4. (Continued)

SYSTEM	PARAMETER	ID	PID	RANGE	REDLINE	BECKMAN	DIGR	OSC	FM TAPE	LOCATION
PUMP PARAMETERS EXTERNAL ' ƆN'T)										
	PUMP DISCH VENT DP	PVDP	063	250 PSID		X	X			FAC
	V650 LH_2 TK P	PLHT	068	200 PSIG		X	X			FAC
	PUMP VENT US P	PUVP	088	5000 PSIG		X				FAC
	PUMP DISCH P	PDP	089	5000 PSIG	X	X	X			FAC
	PUMP INLET P	PHIN1	097	200 PSIG	X	X	X			FAC
TURƆINE PARAMETERS EXTERNAL										
	TURB DISCH T	TTD	023	600 R		X				FAC
	TURB IN T2	TC2	024	600 R		X				FAC
	TURB IN T1	TC1	025	600 R		X	X			FAC
	FAC EXH DUCT T	TFX	029	600 R		X				FAC
	FAC EXH DUCT P	PFX	069	500 PSIG		X				FAC
	TURB STAT DISCH P	PTDS	070	5000 PSIG		X	X			FAC
	TURB TOT DISCH P	PTDT	079	5000 PSIG		X				FAC
	TURB IN TOT P	PTIT	080	5000 PSIG	X	X				T/P
	BEARING SUPPLY P	PBS		5000 PSIG	X	X				
	BEARING SUPPLY T	TBS		25 TO 400 R	X					
	TURB IN STAT PR	PTIS	065	5000 PSIG		X				FAC
SPIN GH_2 SYSTEM										
	GH_2 VENT T-1	TGHV-1	047	600 R		X				FAC
	GH_2 VENT T-2	TGHV-2	048	600 R		X				FAC

TABLE 4. (Concluded)

SYSTEM	PARAMETER	ID	PID	RANGE	REDLINE	BECKMAN	DIGR	OSC	FM TAPE	LOCATION
SPIN GH_2 SYSTEM (CON'T)										
	GH_2 VENT USP	PGH V	071	5000 PSIG		X				FAC
	GH_2 VENT DP	PGHD	061	50 PSIG		X				FAC
	SPIN VLV US P	PSV-1	082	5000 PSIG		X	X			FAC
	SPIN VLV SERVO P	PSV-SER	074	5000 PSIG		X				FAC
	SPIN VLV DS P	PSV-2	106	5000 PSIG	X	X	X			FAC
	SPIN VLV POS	GHSV	055			X				FAC
FACILITY - SPECIAL GH_2 SUPPLY		PGHS	062							
	NAN PWR SUPPLY	PSM-N	038			X				FAC
	LIMA PWR SUPPLY	PSM-L	039			X				FAC
	TEMP REF JUNCT	RJT	049			X				FAC
	LH_2 TK11 P	PHT	087	5000 PSIG		X	X			FAC
	HYDR SUP P	HYD	090	3000 PSIG		X	X			FAC

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calibrated at ice point and LN_2 boiling point and, when applicable, at LH_e boiling point. Thermocouple data are reduced on the basis of the standard NBS millivolt/temperature tables. Thermocouple recorders are electrically calibrated.

With each proximeter used, the spacing between the proximeter and the target material was documented on assembly. On each target of the proximeters, a small notch of a given depth was added that provided a slope of the calibration curve throughout the test. Bench testing of the proximeters and rotor assembly verified the calibration notch concept. A typical example is the signal output for the two radial proximeters used for shaft radial movement at ambient test conditions (Fig. 44). The top of the figure shows the profilometer trace of the slot 0.066 mm (0.0026 inch) deep in 0.785 radians (45 degrees) circumference of the instrumentation nut of Fig. 22. The lower traces show the individual signal output as the shaft is rotated past the two proximeters which are 7.62 mm (0.300 inch) in diameter and spaced orthogonally or 1.571 radians (90 degrees) apart. The calibration curve of the proximeter S/N 002 at ambient conditions, for different radial gap spacings from the shaft nut, shows the linear range of the transducer (Fig. 45). Also note the expected d-c shift due to hydrogen environment temperatures taken from previously tested proximeters with K-Monel targets. The smaller 4.826 mm (0.190 inch) diameter pump-end proximeter probe (P/N ES 91792-02) calibrations on Inconel 718 cartridge target material show a much smaller linear range of signal with gap (Fig. 46) than the larger diameter probe (Fig. 45). This limits the small probe range of measurement capability over that of the larger probe.

Testing

A total of 15 tests was conducted on the turbopump with the hybrid hydrostatic/ball bearing configuration. The summary of the testing is given in Table 5. Hydrostatic bearing data for the tests having significant data are tabulated in Appendix B. During the test series, a total of 1261 seconds of shaft speed rotation was observed with the maximum test speeds near 9215 radians/sec (88,000 rpm) on tests 012 and 014. The tests were run in three series. The first of the series (test 001) was a blowdown test with all instrumentation systems, and start sequencing completed including external flow supply at varied pressure levels on the hydrostatic bearings. No gaseous hydrogen was supplied to the turbine to allow pumping and shaft torque. This allowed the checkout of all instrumentation systems, chilldown, start procedures, and sequencing. The influence of pretest turbine-end hydrostatic bearing supply pressures on the balance piston sump pressures and the axial thrust balancing effects of added flow in the balance piston sump pressure also were determined. The second test series was with turbine GH_2 drive using an external liquid hydrogen flow supply to the hydrostatic bearings. This series included tests 002 through 011. During this test series, shaft speeds were obtained to 8482 radians (81,000 rpm). A wide range of hydrostatic bearing supply pressures to 1882 N/cm^2 (2730 psig) on the turbine end and 758 N/cm^2 (1100 psig) on the pump end was achieved. Bearing supply flowrates were continuously monitored and start acceleration rates were simulated from 628 to 10472 radians/sec/sec (6000 to 100,000 rpm/sec). Also on the last test (011), a simulation of a pump-fed bearing supply or internally supplied flow was achieved with the required settings on the bearing flow controllers previously discussed. On the third test series (tests 012 to 015),

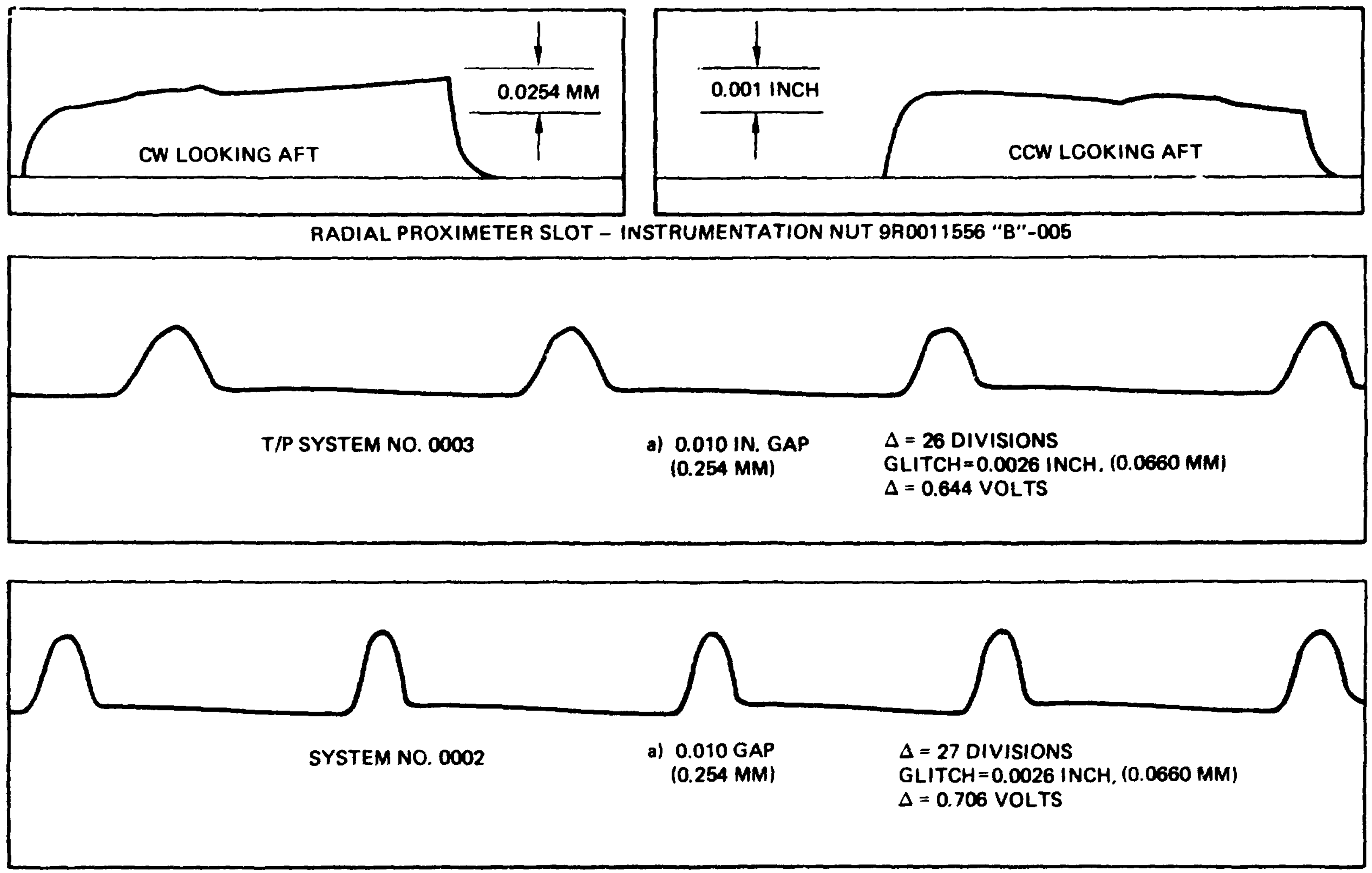

Figure 44. Shaft Radial Proximeters Signal Characteristics

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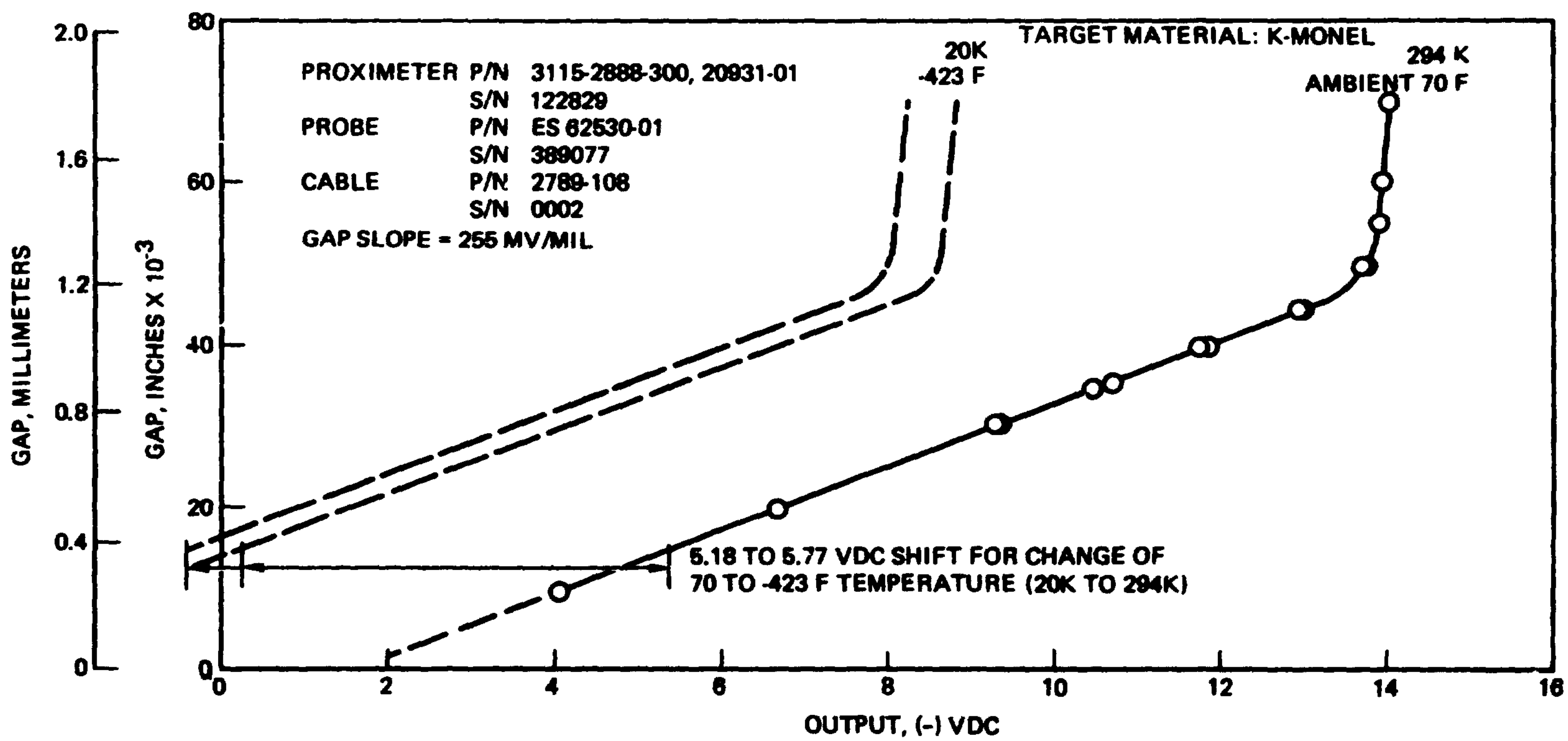

Figure 45. Bently Proximeter Radial Probe Checkout Test Results

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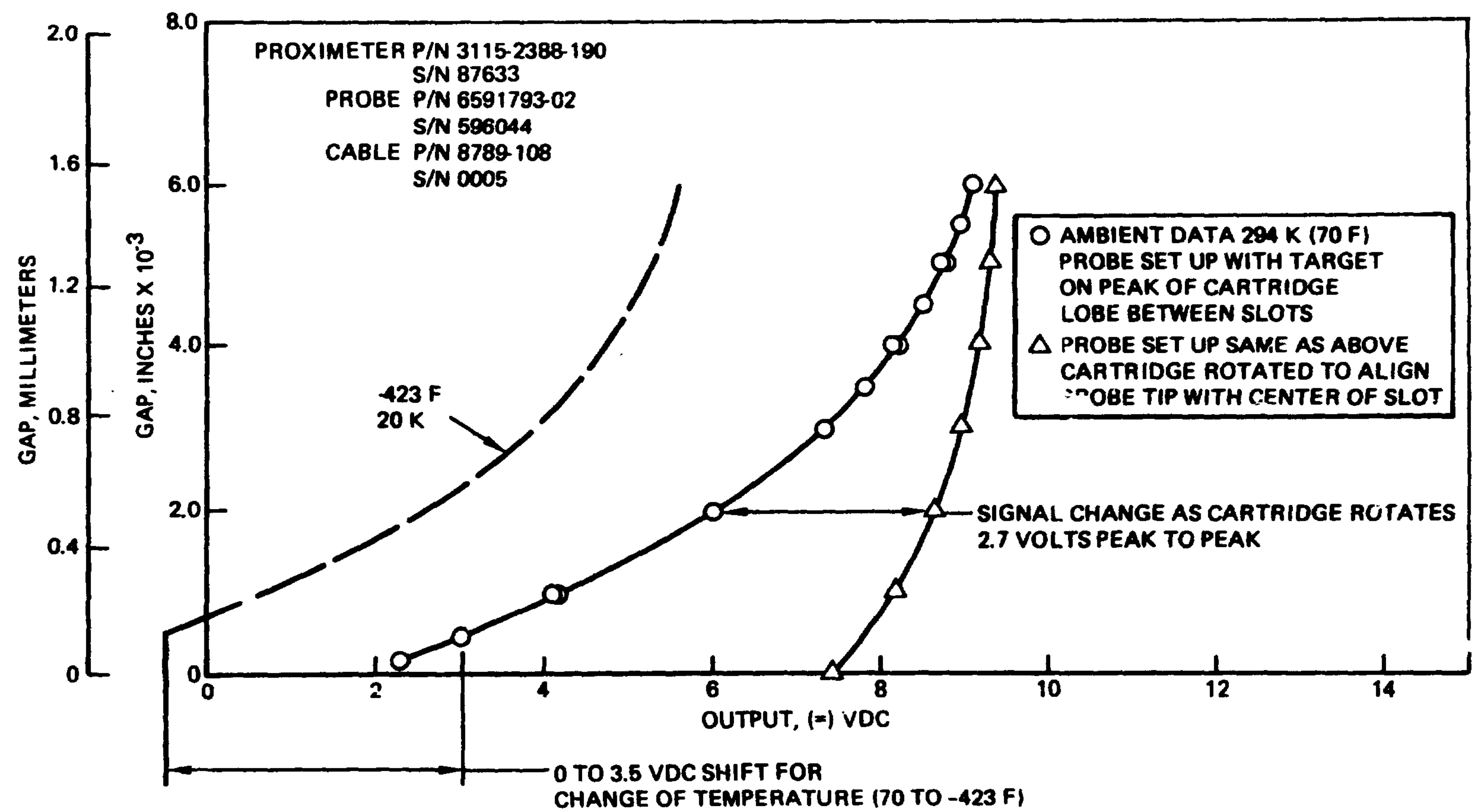

Figure 46. Bently Probe, Pump Cartridge Speed Pickup Checkout Test Results

TABLE 5. MARK 48-F HYBRID BEARING TEST SUMMARY

TEST NO.	DATE TEST	SPEED RPM	TIME, SEC	REMARKS
001	25 MAY	0		BLOWDOWN - CHILLED TO PRESTART CONDITIONS. TURBINE AND PUMP, HIGH-SPEED BEARING MANIFOLD PRESSURES 790 AND 687 PSIG MAXIMUM RESPECTIVELY. SHAFT WINDMILLS TO 1400 RPM - PUMP CARTRIDGE ROTATES. TURBINE CARTRIDGE, NO ROTATION.
002	7 JUNE	0		PUMP START NOT ACHIEVED - INLET PRESSURIZED AND SHAFT WINDMILLING 1800 TO 2100 RPM. PUMP CARTRIDGE ROTATES INTERMITTENTLY.
003	9 JUNE	29,000 (MAX)		PUMP START - SHAFT SPEED AT 28,800 RPM IN 200 MILLISECONDS. INLET PRESSURE DEPRESSED BELOW 85 PSIG AND CUT TEST. PUMP CARTRIDGE SPEED REACHED 8000 RPM IN 1.2 SECONDS.
004	9 JUNE	37,600 (MAX) 25,000	231	PUMP START SHAFT SPEED 29,800 RPM IN 0.7 SECOND MAXIMUM AT 37,680 RPM IN 6 SECONDS. PUMP CARTRIDGE 36,440 RPM IN 7 SECONDS. TURBINE CARTRIDGE TO 2400 RPM IN 1 SECOND THEN BACK TO ZERO. OPERATE 22K-25K RPM FOR 220 SECONDS.
005	14 JUNE	55,700 (MAX)		START CUTOFF DUE TO OVERSPEED TARGET SPEED WAS 30,000, 65,000, AND 50,000 RPM.
006	14 JUNE	33,790	61	START TO 33,790 RPM, HOLD FOR 61 SECONDS (29,000 TO 33,790 RPM) STIFFEN BEARINGS. RAMP SPEED NOT ACHIEVED DUE TO CUTOFF (TURBINE BEARING SERVOVALVE OPEN CUTOFF).
007	14 JUNE	33,600	26	START TO 33,600 RPM, HOLD FOR 25 SECONDS, STIFFEN BEARINGS. (TEST CUT DUE TO PUMP HYDROSTATIC BEARING. SERVOVALVE FULL CLOSED) 29,760 TO 33,600 RPM FOR 25 SECONDS.

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TABLE 5. (CONTINUED)

TEST NO.	DATE TEST	SPEED, RPM	TIME, SEC	REMARKS
008	16 JUNE	32,500 63,000	85 37	START PUMP TO 32,500 RPM IN 1 SECOND. STIFFEN BEARINGS. SPEED RAMP TO 65,000 RPM IN 5 SECONDS. SOFTEN BEARINGS TO MEDIUM.
		48,000	17	SPEED RAMP TO 48,000 RPM IN 10 SECONDS. HOLD 17 SECONDS. CUT TEST. PUMP CARTRIDGE SPEED FOLLOWED SHAFT. TURBINE CARTRIDGE DID NOT ROTATE. ONLY SLIGHTLY AT INITIAL START. (SPIN VALVE REQUIRES REPAIR)
009	23 JUNE	0	0	START CUT DUE TO HIGH INLET TEMPERATURE AFTER SEQUENCE START.
010	23 JUNE	41,500 81,000	60 (MAX) TRANSIENT	START PUMP TO 41,000 RPM IN 7-SECOND RAMP. STIFFEN BEARINGS. ACCELERATE SHAFT TO TARGET 85,000 RPM. REACHED 81,000 RPM WHEN VSC CUT AT 15 G RMS ON PUMP RADIAL ACCELEROMETER. CRITICAL SPEED APPARENT AT 36,000 AND 81,000 RPM. CASING RESONANCE AT 57,000 RPM.
11	30 JUNE	40,000 16,000 29,000 35,000 TRANSIENT AND OTHER	50 10 30 60 220 370	START PUMP TO 40,000 RPM IN 7-SECOND RAMP. SIMULATE PUMP-FED HYDROSTATIC BEARING PRESSURES. SPORADIC TURBINE CARTRIDGE ROTATION PRECLUDES HIGHER SPEED OPERATION. OPERATE FOR 370 SECONDS FROM SPEEDS OF 16,000 TO 56,000 RPM AND 90 TO 122% FLOWRATES. CUT DUE TO PUMP RADIAL ACCELEROMETER EXCEEDING 15 G RMS AT 56,000 RPM (CASING RESONANCE).
012	9 JULY	40,000 40-23,000 23-20,000 20-88,000	57 50 72 8 197	START PUMP TO 40,000 RPM IN 10 SECONDS USING INTERNAL FLOW SUPPLY TO HYDROSTATIC BEARINGS. DECREASE SPEED TO 23,000 IN 50 SECONDS TILL TURBINE CARTRIDGE SPEEDS UP FROM ZERO TO 5600 RPM. HOLD SHAFT SPEED AROUND 20,000 RPM FOR 72 SECONDS. PUMP CARTRIDGE TRACKS SHAFT SPEED, TURBINE CARTRIDGE SPEED VARIES FROM 0 TO 11,500 RPM. SHAFT SPEED INCREASED TO TARGET OF 90,000 RPM. ACHIEVED 33,000 RPM IN 8 SECONDS. PUMP CARTRIDGE ACCELERATES TO 87,500 RPM IN 6 SECONDS THEN DECREASES TO 20,000 RPM BEFORE TEST CUT DUE TO INLET

TABLE 5. (CONTINUED)

TEST NO.	DATE TEST	SPEED, RPM	TIME, SEC	REMARKS
				PRESSURE OSCILLATIONS EXCEEDING MINIMUM REDLINE (75 PSIG). TURBINE CARTRIDGE DELAYS ACCELERATION UNTIL SHAFT SPEED = 73,000 RPM, THEN ACCELERATES TO 35,00 RPM BEFORE TEST CUT. LARGE INLET PRESSURE OSCILLATIONS (LOW FREQUENCY) BEFORE CU . LOST SPEED PROBE AT END OF TEST (PRESSURE RATIO 2.5 AT 88K RPM).
013	9 JULY	51,000 (MAX)	2	TEST CUTOFF AT STAR TEST BY LOW INLET PRESSURE REDLINE (65 PSIG), SHA SPEED ESTIMATED TO 51,000 RPM IN 1.6 SECONDS. PUMP-END CARTRIDGE TO 16,500 RPM, IN 1.9 SECONDS, TURBINE CARTRIDGE TO 5,200 RPM IN 1.9 SECONDS.
014	15 JULY	30,000 74-77,000 77-87,000	71 66 5.8 148	PUMP STARTED TO 30,000 RPM IN 7 SECONDS USING INTERNALLY SUPPLIED FLOW TO HYDROSTATIC BEARINGS. VARIED SPEED 31,000 TO 28,000 RPM OVER 71 SECONDS. TURBINE CARTRIDGE SPEED VARIED 11,000 TO 8500 RPM. PUMP CARTRIDGE TRACKED SHAFT SPEED. INCREASED SHAFT SPEED TO 74,500 RPM IN 5 SECONDS THEN INCREASED TO 77,000 RPM AFTER 25 SECONDS. TURBINE CARTRIDGE SPEED TO ZERO AT FIRST ACCELERATION AND STAYED. PUMP CARTRIDGE TRACKED TO 52,000 RPM AND SLOWLY WORKED UP TO 64,000 RPM WITH INDICATIONS OF DECELERATIONS THROUGHOUT PERIOD. SPEED INCREASED TO 87,000 RPM IN 5.8 SECONDS. PUMP CARTRIDGE SLOWLY WORKED ITS WAY TO ZERO IN 2.6 SECONDS. TURBINE CARTRIDGE STARTED ACCELERATION FROM ZERO AT SHAFT SPEED = 81,000 RPM AND ACCELERATED TO 22,200 RPM IN 2.2 SECONDS, THEN DECELERATED TO ZERO IN 0.5 SECONDS. DECELERATION STARTED 2.3 SECONDS BEFORE CUTOFF AT A SHAFT SPEED OF 86,000 RPM (PRESSURE RATIO: TURBINE = 2.9 AT 76K RPM).

TABLE 5. (CONCLUDED)

TEST NO.	DATE TEST	SPEED, RPM	TIME, SEC	REMARKS
015	15 JULY	0	0	START ATTEMPTED TO 30,000 RPM IN 2 SECONDS USING INTERNALLY SUPPLIED FLOW TO HYDROSTATIC BEARINGS. ALTHOUGH TURBINE GH_2 SUPPLY PRESSURES EQUIVALENT TO 55,000 RPM APPLIED TO TURBINE, NO SHAFT TURNING OCCURRED. AFTER 2.5-SECOND TEST CUT DUE TO 20 G RMS RADIAL ACCELEROMETER VIBRATION LEVELS. POSTTEST AMBIENT TORQUE CHECKS SHOWED SHAFT TURNING FREELY.

internal pump-fed bearing supply flows were used. Turbine-end bearing supply pressures using a pump discharge supply source were achieved to 2413 N/cm^2 (3500 psig) and pump-end supply pressures fed from the first-stage impeller front shroud tapoff source achieved a supply pressure of 655 N/cm^2 (950 psig). Shaft speeds in excess of 9110 radians/sec (87,000 rpm) were achieved on tests 012 and 014. In these tests, the bearing supply flowrates were individually measured by routing the tapped off pump source flows through the flow-measuring orifices prior to routing the flow into the supply lines.

A summary of the individual tests with their objectives, duration, problems, and accomplishments follow. Reduced data points of each test having valuable data can be found in Appendix B.

Test 001. This test was a blowdown test at chilled conditions with the objectives of checkout out the chilldown procedures, and turbopump test sequencing up to, but not including, a startup with turbine GH_2 supply pressure. Four major checkouts were required: (1) the hydrostatic bearing supply temperature levels from the external tank supply, (2) the balance piston sump pressure levels as a function of hydrostatic bearing supply pressure, (3) the pump bearing sump pressure level as a function of bearing supply pressure, and (4) a checkout of all the instrumentation including the Beckman data acquisition and all other recording devices. The test started with increased inlet pressure from 28 N/cm^2 (40 psig) to 65 N/cm^2 (95 psig) over 120 seconds. During this time, the shaft windmill speed varied from 21 radians/sec (200 rpm) to 147 radians/sec (1400 rpm) and the hydrostatic cartridges rotated intermittently. Pressurization of the hydrostatic bearings external supply tank (tank 11) was increased to 3170 N/cm^2 (4600 psig). The pump bearing manifold pressure increased to a maximum 474 N/cm^2 (687 psig), while the sump pressure increased only 7 N/cm^2 (10 psi) over inlet pressure. The turbine bearing manifold pressure increased to 545 N/cm^2 (790 psig), while the balance piston sump pressure increased to 92 N/cm (133 psig) or 26 N/cm^2 (38 psi) over inlet pressure. During this time, the axial Bently showed the shaft moved forward as expected due to the pressure in the balance piston sump. Corrections in procedures developed by the test results were the chilldown procedures and pressures used which resulted in reduced LH_2 usage of chilldown. Also, the hydrostatic bearing supply pressure controllers were found to require increased response rates to keep up with the tank 11 pressurization. Data acquisition problems were corrected and pressure controller systems monitoring were improved. This test was very successful.

Test 002. This test was the first attempt to start the turbopump with GH_2 drive gas. The objectives were a checkout test with the initial startup to 3665 radians/sec (35,000 rpm) with each of the hydrostatic bearing supply controller pressures set at 103 N/cm^2 (150 psi) above the reference turbopump pressures (first-stage impeller discharge pressure for pump end and pump discharge pressure for turbine end). The test went well until the tank 11 pressure was increased prior to start to 1682 N/cm^2 (2440 psig) when the redline for the pump bearing flow controller valve position cut the test by indicating the supply valve was closed. This indicated further controller open-close redline analysis was required and the system test control was further modified in an effort to minimize unnecessary test redline cutoffs from the controller system.

Test 003. This test was a checkout test similar to test 002 to achieve the following: (1) startup checkout with hybrid hydrostatic bearings to 3665 radians/sec (35,000 rpm), (2) checkout balance piston axial thrust control, (3) checkout hybrid bearing behavior at startup and through first and second predicted critical speeds, and (4) checkout facility capability for control of turbopump and hydrostatic bearing. The turbopump started up very fast and reached a speed of 3037 radians/sec (29,000 rpm) in 200 milliseconds; the pump cartridge speed accelerated to 837 radians/sec (8000 rpm) in 1.2 seconds. After that, the test was cut automatically due to a low inlet pressure redline. This was due to the rapid acceleration of the turbopump reducing the inlet pressure below the cavitation redline. The speed control system that allowed the high start acceleration was checked out and corrected.

Test 004. This test was designed to complete the objectives of test 003 and achieve extended running time on the bearings at low speed. The start was still very rapid with shaft speed to 3120 radians/sec (29,800 rpm) in 0.7 second and then to 3946 radians/sec (37,680 rpm) in 6 seconds. The turbine cartridge went to 251 radians/sec (2400 rpm) in 1 second and then back to zero in 3 seconds. The pump cartridge accelerated to the shaft speed of 3921 radians/sec (37,440 rpm) in 7 seconds. The hydrostatic bearing supply manifold pressures at the controllers were set to 103 N/cm^2 (150 psi) over reference pressure at start. After startup, the speed was reduced to 2308 to 2618 radians/sec (22,000 to 25,000 rpm) and held for 200 seconds. The controlled hydrostatic bearing supply reference delta pressure was raised to 552 N/cm^2 (800 psi) and 700 N/cm^2 (1015 psi) for the pump and turbine end, respectively. Near the end of the test, the speed was reduced to 1910 radians/sec (18,240 rpm) for approximately 20 seconds. During the test, the pump cartridge followed shaft speed while the turbine cartridge did very little rotating. During the test, the speed was manually changed over a small range in an attempt to see if the turbine-end cartridge might begin to rotate. It should be noted that the hydrostatic bearing supply pressures were controlled nicely with the control system providing adequate response with speed changes and tight control of the values desired.

Test 005. The objectives of this test were to operate to speeds of 6807 radians/sec (65,000 rpm) and to get test data at very stiff and medium stiff hydrostatic bearing pressures, and also, to verify axial thrust control at high speeds. On test 005, the start was targeted to 3141 radians/sec (30,000 rpm) but was cut due to an erroneous overspeed signal to 5864 radians/sec (56,000 rpm). The speed was thought to be erroneous because of the low turbine drive inlet pressures recorded. Pump-end cartridge acceleration was to 1528 radians/sec (14,590 rpm) in 1.40 seconds.

Test 006. This test had the same objectives of test 005. The shaft speed reached was approximately 3560 radians/sec (34,000 rpm) at start and was held in that range for ~61 seconds. The shaft speed output in the test indicated a very erratic condition. This was due to signal conditioning circuitry and attempts to correct it as the test progressed failed. During the test, the pump cartridge tracked the shaft but the turbine cartridge showed little rotation. At the latter part of the test, supply pressure levels were increased from 159 N/cm^2 (230 psi) to 579 N/cm^2 (840 psi) above reference pressure for the pump bearing and from 276 N/cm^2 (400 psi) to 758 N/cm^2 (1100 psi) above reference pressure for the turbine bearing. Cutoff occurred due to the turbine bearing flow controller servovalve reaching its redline full-open position. This was caused by inadequate pressure in the tank 11 supply for the very high supply pressures required. After the test, procedures for repressurizing tank 11 and correction of the shaft speed circuitry were initiated.

Test 007. The objectives of this test were to extend the speed of test C06 to a speed of 6807 radians/sec (65,000 rpm). The turbopump was run to 3519 radians/sec (33,600 rpm) for 25 seconds at the preset bearing supply pressures. Attempts to increase the supply pressures by first increasing tank 11 pressure resulted in the pump bearing valve indicating full closed due to the high tank 11 pressures existing and the high pressure drop required across the servovalve. The redlines set on the valves were to protect the system from losing control of the hydrostatic supply pressures. The problem arose that for high pressure drops, the valves would approach fully closed to within less than 5% open. When this happened, the position monitor device did not have enough sensitivity to read the last 5% on closure position and, as a result, activated the redline. The review of the redlines indicated that these servovalve close and open redlines could be deleted if other test procedure precautions and redlines were incorporated, which was done. At this point in the testing, the pump cartridge speed tracked the shaft well. The turbine cartridge did not track but, on occasion, had rotated some as higher bearing supply pressures were used and higher speeds were reached. From the data analysis the indications were that at higher shaft speeds, the balance piston axial position would be more favorable to the turbine cartridge end clearance and the cartridge would begin to rotate with the shaft.

Test 008. This test was very successful from a standpoint of operating time and areas covered in speed and hydrostatic bearing pressure ranges. The object of the test was to obtain a maximum speed of 6807 radians/sec (65,000 rpm) and obtain a wide range of hydrostatic bearing operating conditions. The turbopump operated for 140 seconds at three basic speed levels of 3403, 6597, and 5027 radians/sec (32500, 63000, and 48000 rpm). A trace of the operating conditions of the hydrostatic bearings pressures is given in Fig. 47. The data plotted are the operating levels of the pump and turbine-end hydrostatic bearing supply pressures (which are controlled by the supply pressure controllers as described) as a function of pump speed. The figure shows the supply pressures at 1 start, increasing with speed to the first operating point 2 at 3299 radians/sec (31,500 rpm), then increasing the two hydrostatic bearing supply pressures to higher values at point 3, then again to higher values 4 and back to lower values 5 again. (Note: The pump-end supply maximum pressure limit of 758 N/cm^2 (1100 psig) was maintained while the turbine-end bearing pressure was varied.) The pump shaft speed was then increased with the turbine-end hydrostatic bearing supply pressure tracking reference pressure to point 6 where the tank 11 supply pressure matched turbine-end supply pressure 7. The speed was held at around 6702 radians/sec (64,000 rpm), while the hydrostatic pressure reduced slowly to 1172 N/cm^2 (1700 psig) 8. The shaft speed was then slowly reduced to 5027 radians/sec (48,000 rpm) 9 and held constant as the supply pressure further reduced to 827 N/cm^2 (1200 psig) for the turbine

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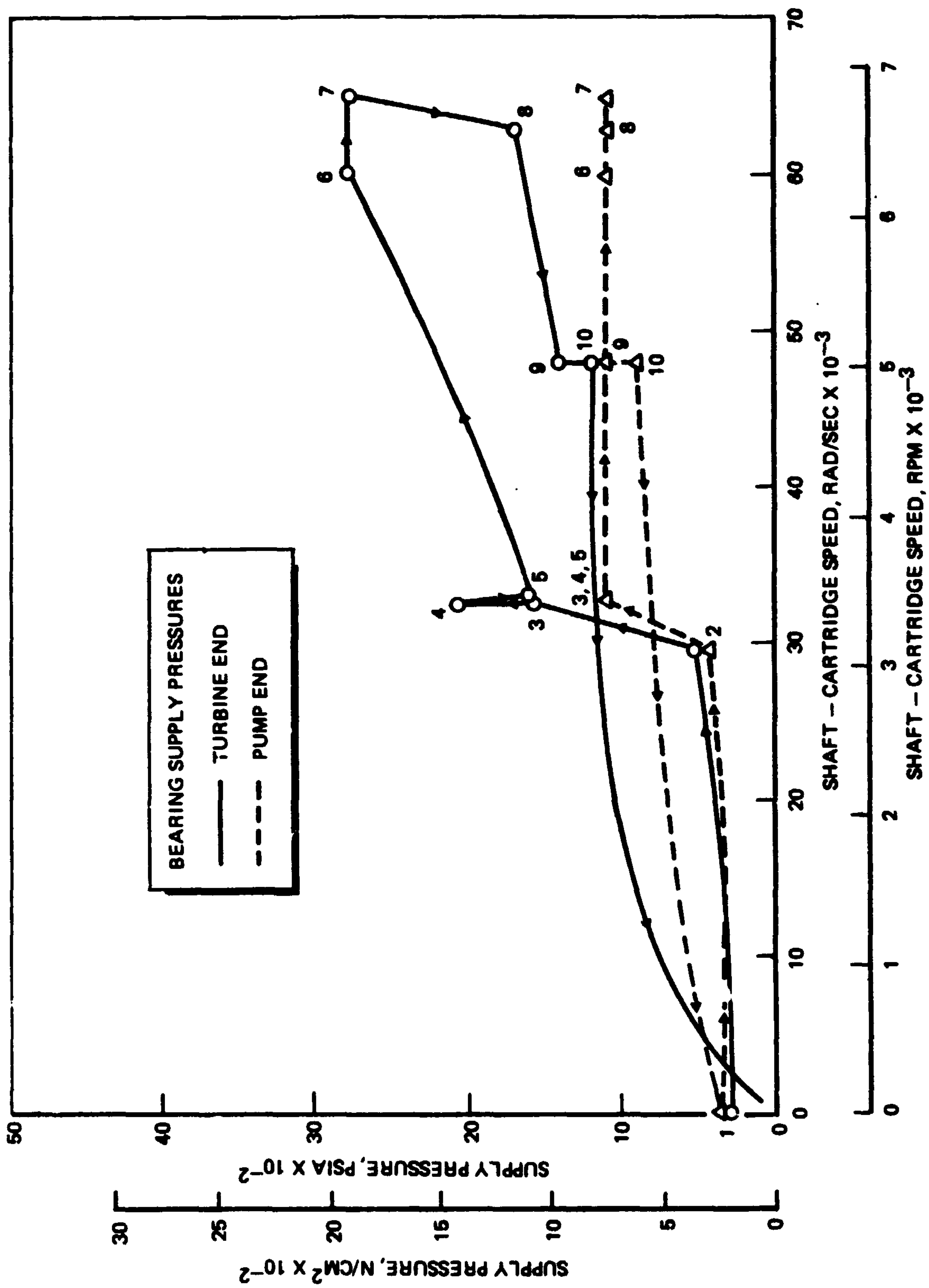

Figure 47. Turbopump Hydrostatic Bearing Supply Pressures - Test 008

bearings and 655 N/cm^2 (950 psig) for the pump-end bearings (10). The test was then termirated with the shaft speed going to zero.

During the test, the pump-end cartridge followed the shaft speed at all conditions. The turbine-end cartridge began rotation at start but returned to zero speed approximately 1.8 seconds into the test. An interesting correlation of turbine-end cartridge rotation has been developed from the two proximeter measurement outputs for the shaft axial position and the turbine cartridge rotation, as shown in Fig. 48. The time expanded and correlated data show the plot of shaft axial position as measured from the axial Bently proximeter shown. Also shown in Fig. 48 is the movement signal of the turbine cartrdige as each of the eight flat faces of the cartridge face registers a peak on the trace. The results show the shaft moves forward toward the pump end at startup approximately 0.305 mm (0.012 inch) and then eventually back to approximately 0.229 mm (0.009 inch). At this point, the aft movement allows the turbine cartridge freedom to accelerate for 330 revolutions of the shaft, which it does until the shaft starts to move slightly forward axially. When this happens, the turbine cartridge speed quickly tails off and stops within 280 shaft revolutions. Throughout the test, the turbine cartridge occasionally changes its clocking, but only at a very low and erratic frequency. These data show hard evidence that the shaft forward movement does not allow the turbine cartridge to rotate. Further analysis of the shaft movement to the higher speeds (shown in Fig. 49) indicates the pump end of the shaft moves aft nearly 0.051 mm (0.002 inch) as speed increases and at shutdown moves gently back to the backstop. During these shutdown transients, the turbine-end cartridge on some tests had shown some slight rotation as well. It should be noted that on test 008, a critical speed was detected at approximately 3665 radians/sec (35,000 rpm). Also on this test, a casing resonance was seen at about 950 Hz with a maximum amplitude of 12 g at a speed of 5969 radians/sec (57,000 rpm) as the speed was being reduced to 5027 radians/sec (48,000 rpm). The dynamic activity of each test will be reported in the dynamic analysis section of this report.

Test 009. The objectives of test 009 were to test the hydrostatic bearing turbopump at speeds to 9634 radians/sec (92,000 rpm) while operating at very stiff and medium stiff supply pressure levels on the hydrostatic bearings. Verification of turbopump axial thrust control was an initial check to be made at high speeds before the test could proceed. This was done by setting redlines on the balance piston cavity and pump pressures based on previous test data and current analysis. Test 009 was cut off on a high inlet temperature redline at startup and no usable data were generated.

Test 010. The objectives of test 010 were similar to those of test 009. The planned procedure was to start with medium level supply pressures on the hydrostatic bearings of 128 N/cm^2 (185 psi) above reference for the turbine supply and 193 N/cm^2 (280 psi) above reference for the pump-end supply. This was done and the shaft speed was raised to 4294 radian/sec (41,000 rpm) in approximately 7 seconds. While holding a constant speed, the bearings were pressurized to high stiffness 1586 N/cm^2 (2300 psig) on the turbine end and 758 N/cm^2 (1100 psig) on the pump end). The shaft speed was increased to 8482 radians/sec (81,000 rpm) while targeting for 8901 radians/sec (85,000 rpm). At this point, the test was

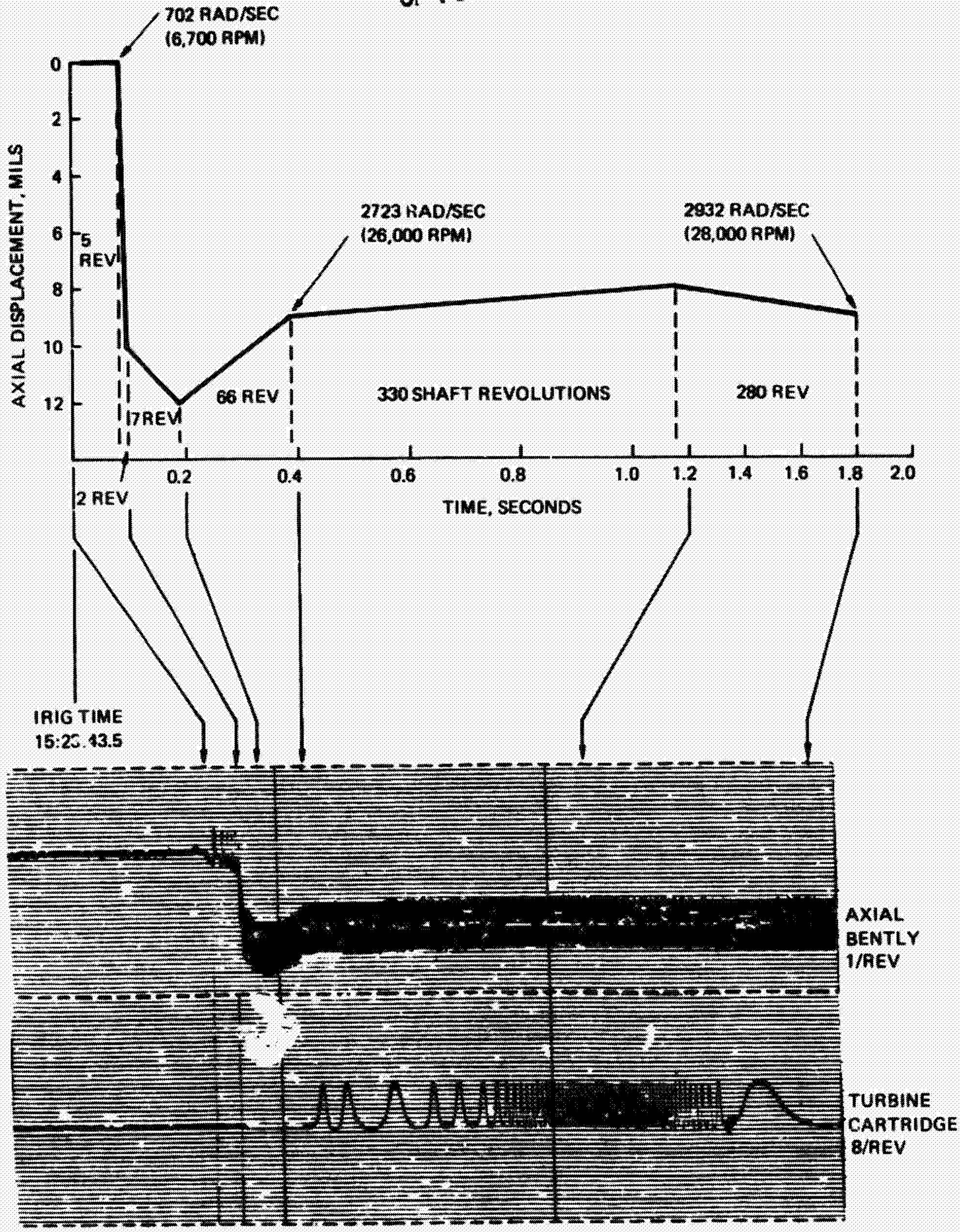

Figure 48. Shaft Displacement - Startup Transient Characteristics - Test 008

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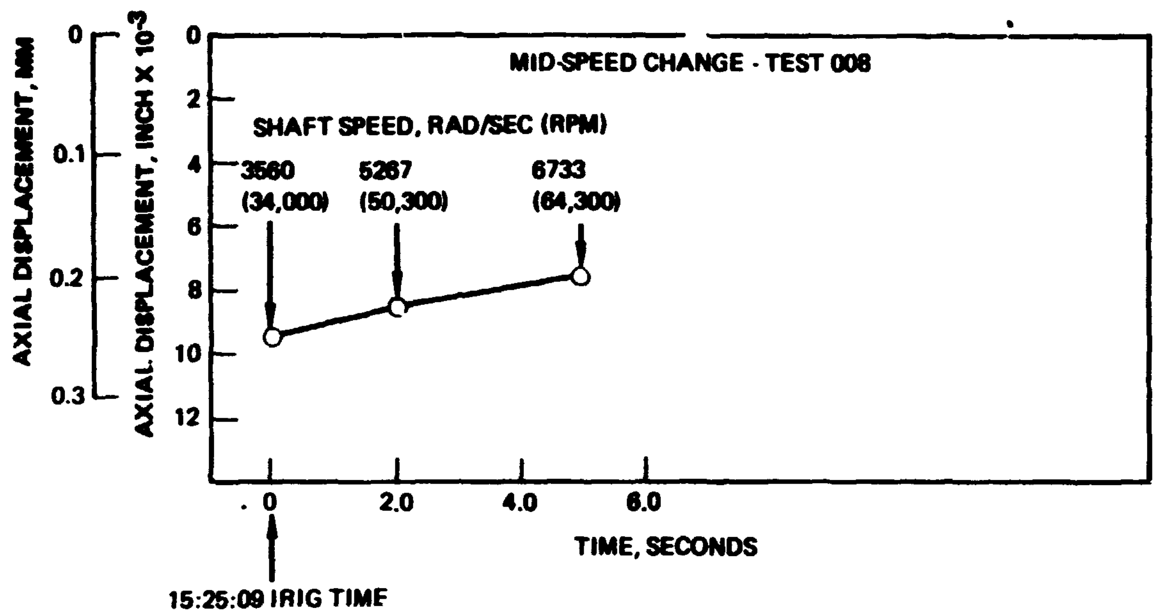

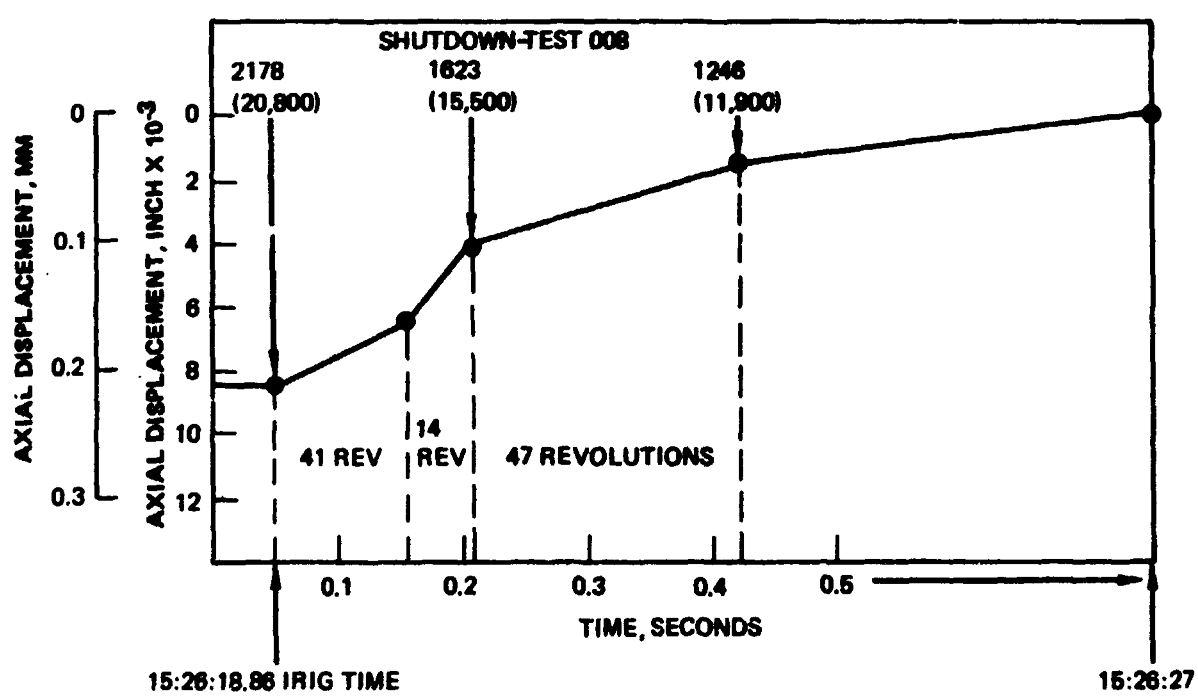

Figure 49. Shaft Displacement, Mid-Speed and Shutdown - Test 008

cut due to the redline vibration safety cutoff (VSC) circuit by pump radial accelerometers registering a vibration level greater than 15 g. The data show critical speed levels of 3770 radians/sec (36,000 rpm) and 8482 radians/sec (81,000 rpm) and a casing resonance at 5970 radians/sec (57,000 rpm). The turbine cartridge rotation was negligible through the test, and the pump-end cartridge showed evidence of an inability to track shaft speed at the speeds above 7330 radians/sec (70,000 rpm). The shaft and pump-end cartridge speed are shown in Fig. 50. The data show that during the shaft acceleration from 4294 radians/sec (41,000 rpm) to high speed, the pump-end cartridge tracked shaft speed very well initially. At a shaft speed of 7435 radians/sec (71,000 rpm), the pump cartridge speed decelerated as if it had rubbed the bearing wall and then quickly recovered speed and tracked the shaft to 7750 radians/sec (74,000 rpm), when it quickly decelerated again as if it had touched the bearing wall. Touching is indicated by the radial Bently proximeter traces at the points of first, second, and third cartridge decelerations. At this point, the cartridge did not return to shaft speed but found an intermediate speed of 5760 radians/sec (55,000 rpm) and operated there with minor fluctuations until the test cut off due to excessive vibration levels. Note also in Fig. 50 that the cartridge increased its speed at cutoff until the shaft speed matched it and then both decelerated together. These data are closely analyzed and reported in the Dynamic Analysis section of this report.

Test 011. The objectives of this test were to operate at an increased turbine pressure ratio in an attempt to change the balance piston axial thrust position. This was to provide added end play to the turbine cartridge to allow it to rotate. The pressure ratio was changed from 1.5 to 2.0 by decreasing the turbine downstream exhaust resistance. The estimated axial thrust change of turbine was 4893 N (1100 pounds). An additional objective was to operate at hydrostatic bearing pressure levels so as to simulate internal (turbopump fed) supply conditions. The test was begun with the hydrostatic bearing supply pressures set at less than 68 N/cm^2 (100 psi) above respective reference pressures on pump and turbine bearings. This was the minimum flow to keep the bearing temperatures at respectable start conditions. The turbopump start brought the speed to 4189 radians/sec (40,000 rpm) in 3 seconds, and the bearing pressures were then reduced to simulate pump-fed conditions. After startup, the turbine cartridge showed very little signs of rotation. As a result, the speed was varied from 4189 radians/sec (40,000 rpm) to 1675 radians/sec (16,000 rpm) and the flowrates were varied from 90 to 122% of nominal with very little effect on turbine cartridge rotation. The speed was then increased slowly to 5864 radians/sec (56,000 rpm) where the test was cut due to excessive vibration levels caused by the previously mentioned housing resonance. During this test, the pump-end cartridge tracked the shaft speed while the turbine cartridge rotation was sporadic and at very low speed when turning, although some slight improvement in cartridge rotation was evident.

The results of test 011 indicated some improvement in turbine cartridge rotation and dictated further increases in the turbine pressure ratio to approximately 2.5 for shaft-balance piston repositioning. Conversion to the internally fed hydrostatic bearing pressure supply was also initiated. This entailed tapping off the pump discharge line and routing the flow through the pressure controller and flow

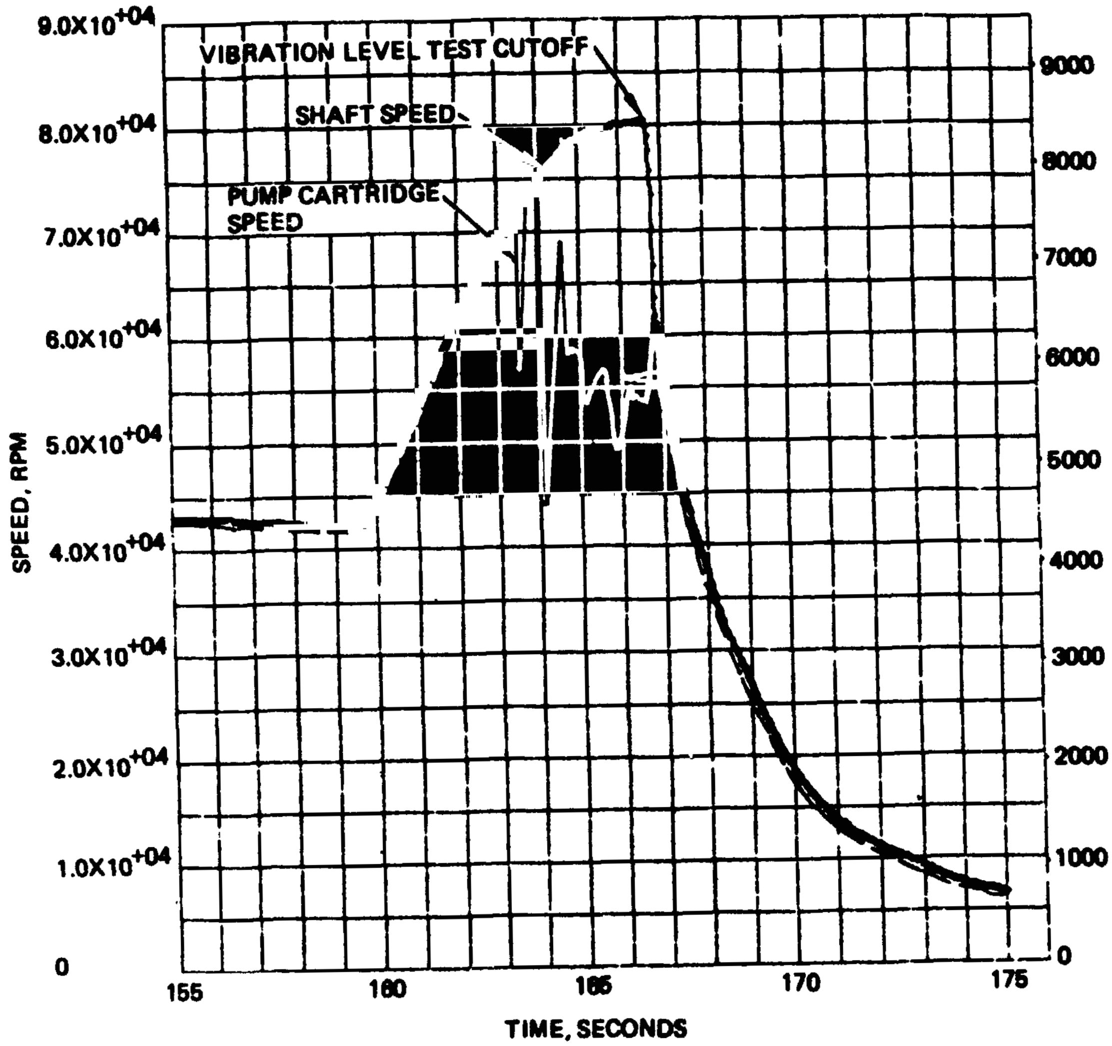

Figure 50. Shaft and Pump-End Cartridge Speed - Test 010

measurement orifice before entering the turbine bearing supply lines. The pump supply was taken from eight first-stage impeller discharge tapoff lines manifolded together, then routed through the pressure controller and flow measurement orifice before entering the pump-end bearing supply lines. The pressure controllers were locked open (not used) and an overboard drainline was inserted into the recirculation loops to facilitate childown. These drains were closed during test.

Test 012. The objectives for this test were to operate with internally recirculated supply flow to the hydrostatic bearings as previously described. The plan was to start to an intermediate speed, verify the balance piston operation and turbine cartridge rotation, then increase speed to 9924 radians/sec (90,000 rpm) and get some operating time at high speed. The pump start was successful to 4189 radians/sec (40,000 rpm) in 10 seconds. The shaft speed was then varied down to 2094 radians/sec (20,000 rpm) to attempt to get the turbine cartridge to speed. At this level, the turbine cartridge speed varied from zero to 1204 radians/sec (11,500 rpm). The speed was then increased toward a target speed of 9425 radians/sec (90,000 rpm) in 10 seconds but, in 8 seconds, when the shaft speed reached 9215 radians/sec (88,000 rpm), the test was terminated due to facility ducting low-frequency pressure oscillations. During the acceleration, the pump cartridge tracked the shaft speed for 6 seconds to 9163 radians/sec (87,500 rpm) then dropped to 2094 radians/sec (20,000 rpm) before test cutoff. The turbine-end cartridge delayed acceleration until a shaft speed of 7645 radians/sec (73,000 rpm) and then accelerated to 3665 radians/sec (35,000 rpm) before test termination. The increased pressure ratio on the turbine to 2.5 at 9215 radians/sec (88,000 rpm) helped the end play problem with the turbine cartridge but not enough to allow completely free rotation. The hydrostatic bearing supply pressures from the internally fed system worked as expected.

Test 013. On this test, the speed probe that reads the shaft speed would not provide an output signal and the test was terminated due to shaft high-speed accelerations causing a low inlet pressure redline cutoff. During this start, the shaft is estimated to have reached 5340 radians/sec (51,000 rpm) in 1.6 seconds. The pump-end cartridge accelerated to 1728 radians/sec (16,500 rpm) in 1.9 seconds and the turbine cartridge accelerated to 544 radians/sec (5200 rpm) in 1.9 seconds. These data indicated the turbine cartridge was rotating more freely with the higher turbine pressure ratio. The speed probe was found to have gone bad at the shutdown of test 012 when chilled. It operated satisfactorily during ambient conditions in pretest checks of test 013, but would not function at LH_2 temperatures.

Test 014. The objectives of test 014 were to test the turbopump to 9425 radians/sec (90,000 rpm) with the internally fed hydrostatic bearings. This was to be done in three speed steps of 3141, 7854, and 9425 radians/sec (30,000, 75,000, and 90,000 rpm) with balance piston operation and cartridge rotation verified at each speed. All three speed levels were generally achieved. The pump was started to 3141 radians/sec (30,000 rpm) in 7 seconds. The speed was varied between 3246 to 2932 radians/sec (31,000 to 28,000 rpm). Turbine cartridge speed varied from 1152 to 890 radians/sec (11,000 to 8500 rpm). The pump cartridge tracked shaft speed. After 71 seconds, the shaft speed was increased to 7959 radians/sec (76,000 rpm). The turbine cartridge speed went to zero and remained. The pump cartridge tracked to 5445 radians/sec (52,000 rpm) and eventually worked its way up to 6702 radians/sec (64,000 rpm) although indications of touching decelerations occurred throughout the 66 seconds of operation at this condition. The speed of the shaft was then increased to 9111 radians/sec (87,000 rpm) in 5.8 seconds. During this time, the pump cartridge worked its way to zero rpm in 2.6 seconds. While the pump cartridge was decelerating to zero, the turbine cartridge speed increased from zero to 2639 radians/sec (25,200 rpm) in 2.2 seconds, then immediately dropped back to zero in 0.5 second. During this period of speed increase, the vibration levels were increasing and the vibration safety cutoff redline of 20 g rms was reached, causing shutdown. The supply pressure levels of the hydrostatic bearings at maximum speed reached maximum values of 607 N/cm^2 (880 psig) for the pump-end bearing and 2261 N/cm^2 (3280 psig) for the turbine-end bearing. It should be noted that much more turbine cartridge rotation was achieved at the highest turbine pressure ratios of this test. This indicates that the balance piston axial position was such as to nearly provide free end play for the turbine cartridge at the highest speeds indicate the limits on clearance may be reached; however, it is mainly tied to the large amplitude of vibration levels encountered at these speeds. The dynamics of this test ill be fully developed in the Dynamics Analysis section of this report.

Test 015. This test was attempted immediately following the test 014 in an effort to achieve more operating time at high speeds in the 9425 radians/sec (90,000 rpm) range. The pump start sequence was initiated, but the shaft would not rotate although a high turbine inlet pressure equivalent to 5760 radians/sec (55,000 rpm) was supplied to the turbine. The test was terminated due to high vibration levels 2.5 seconds after the turbine drive pressure was applied. The data indicated no rotation. Posttest torque checks after the turbopump warmed up to ambient temperatures indicated both the shaft and cartridges would rotate relatively easily. Some slight rubbing sounds were emanating from the turbine tip and labyrinth seals during rotation. At this point, the major objectives of the program had been achieved. A major teardown and inspection was required before further testing would be beneficial. As a result, the turbopump was removed from the test stand for disassembly and inspection.

Turbopump Disassembly — Mechanical Performance

At the end of the testing, the turbopump disassembly and inspection provided interesting information regarding the condition and mechanical performance of the test hardware. After removal from the test stand, the turbopump was returned to the Engineering Development Laboratory at Rocketdyne. Insulation was removed and the turbopump was pressure checked to confirm instrumentation line integrity. The balance piston cavity pressure line was found to have been damaged during disassembly and needed repair for a leak. Torque checks were performed on the shaft after removal of the cartridge speed proximeters. A cross section of the turbopump is given in Fig. 1. With the turbopump shaft horizontal, the torque was 11.3 to 17 N-cm (1.0 to 1.5 in.-lb), with the pump hydrostatic cartridge rotating intermittently with the shaft. A slight radial pressure on the pump cartridge resulted in increased torque to 17 to 45 N-cm (1.5 to 4.0 in.-lb). The turbine cartridge did not rotate with the shaft rotation when the pump centerline was either horizontal or vertical, but did not indicate it was frozen or bound up. The slightly increased torque levels over the build values probably indicate the resistance due to the impeller labyrinth seal and turbine seal damage found during the disassembly.

The first- and second-stage turbine wheels were removed (Fig. 51). The tip seals showed excessive rubbing, as did the interstage seal on both wheel sides. No galling or fretting was observed in the turbine end to shaft attachment surfaces. The shaft torque checks taken after turbine wheel removal were between 5.6 to 11.3 N-cm (0.5 to 1.0 in. lb) in all shaft positions and represents the same values found in pretest assembly. The push-pull test was made on the pump with the shaft position measured as a function of load. The results duplicated the [illegible] the pretest push-pull within 0.025 mm (0.001 inch) (Fig. 30). Removal of the turbine seal and inspection showed a slight rubbing evident on the shaft circumference (Fig. 52), but no sign of wear or scoring, except for light chatter marks indicating some intermittent rubbing pattern.

Removal of the aft rub ring of the turbine cartridge showed only slight, even rubbing with no scoring of the bearium B10 rub ring or Inconel 718 cartridge. At this point, the radial shaft movement side to side was measured. The total movement without high radial load was 0.1397 mm (0.0055 inch) at the pump end and 0.1422 mm (0.056 inch) at the turbine end. This is close to that expected as the pump end diametral clearance of the bearing was 0.1245 mm (0.0049 inch) and the outer race of 0.0330 mm (0.0013 inch), for a total of 0.1575 mm (0.0062 inch). Similarly, the turbine end values of 0.1143 mm (0.0045 inch) and 0.0356 mm (0.0014 inch) respectively combined for a total of 0.1473 mm (0.0058 inch). The radial play was not recorded during the turbopump build, but may be a measurement useful for subsequent builds. The indications are that the static build radial play did not change through the testing.

The shaft stackup was disassembled by stretching the centerbolt and releasing the stretching nut. The shaft length change was measured at 0.457 mm (0.018 inch) and found to agree with that of the assembly. Next, the shaft bolt was drawn out of the impeller stack from the turbine end using a maximum force of 3336 N (750 pounds). The pump-end bearings pull off the shaft in this process, and the turbine-end bearings stay with the shaft. At disassembly, the pump-end and turbine-end hydrostatic bearings were inspected in detail.

The pump-end hydrostatic cartridge outside diameter showed broad, dark streaking lines around the circumference of the cartridge, as shown on the left of Fig. 53. One section at the front end was mottled and microscopic examination showed slight amounts of silver flattened against the chrome plating in this area. No chrome plating is missing on the part. Examination of the dark brown sections showed them to be more of a discoloration th a surface defect. There are also some evenly spaced discolored spots that correspond to the hydrostatic bearing orifice location and size, which indicates the discoloration may be caused by a substance in the liquid hydrogen flow. The pump-end bearing showed signs of slight rubbing at the forward end of the bearing between the pad row and the pump-end exit of the fluid film. This rubbing is evident at 11 to 2 o'clock and 5 to 7 o'clock, as shown in Fig. 54. Light rubbing also occurs aft of the front pad row Profilometer data on the deepest section of rubbing indicate a material removal of approximately 0.0008 mm (0.0003 inch) deep at the

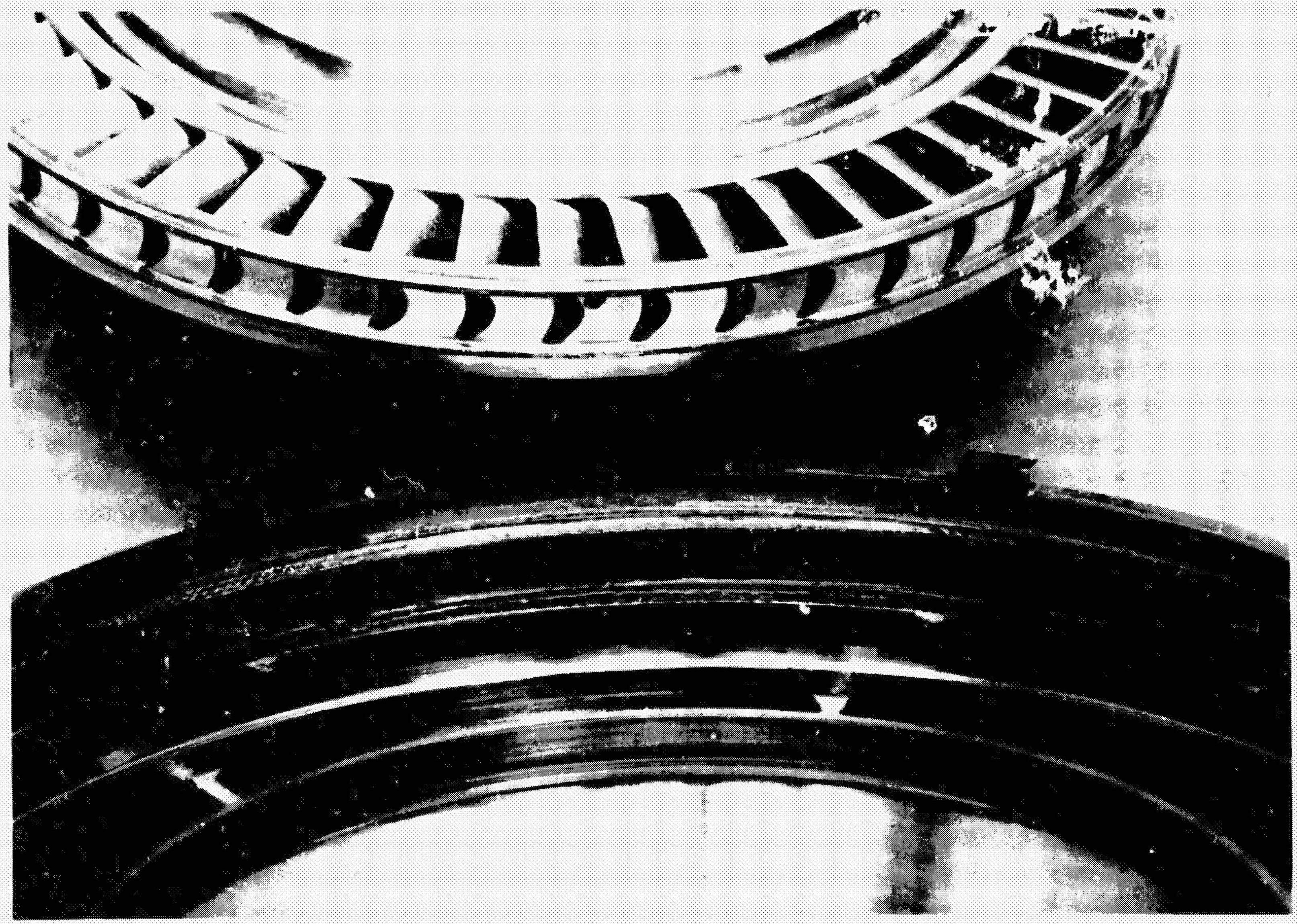

Figure 51. Turbine Tip Seal Damage

Figure 52. Turbine Shaft Seal and Cartridge Condition at Disassembly

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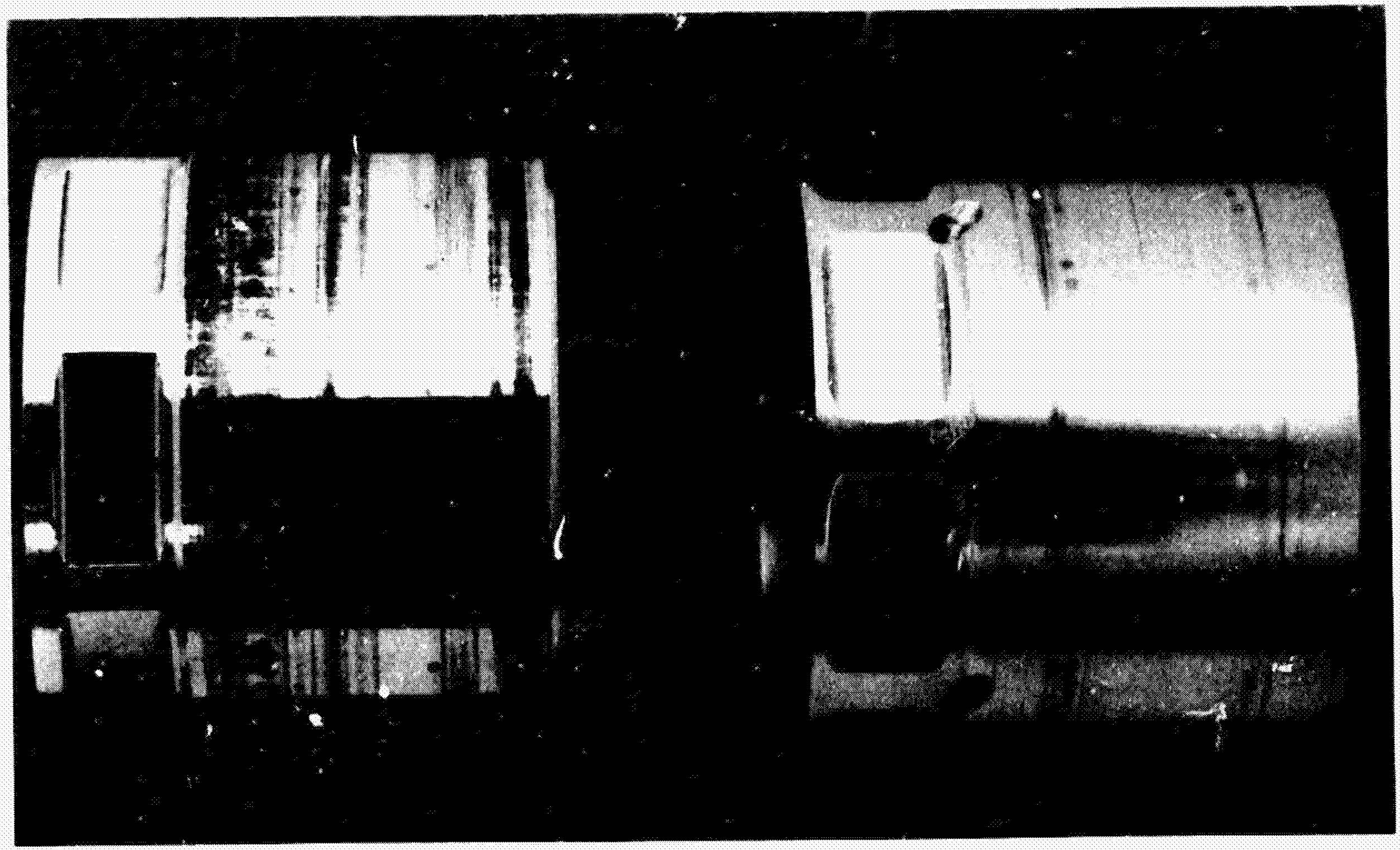

PUMP END

TURBINE END

1XZ95-8/10/82-C1J*

Figure 53. Mark 48-F Hydrostatic Bearing Cartridges After Test

1X295-8/10/82-C1C*

Figure 54. Pump-End Hydrostatic Bearing After Test

front of the bearing for a length of 2.54 mm (0.100 inch), and a buildup of material of 0.0102 mm (0.0004 inch) for a length of 2.54 mm (0.100 inch) just aft of that. Further aft, over the rest of the bearing axial length, there was no material transfer. The majority of the light rubbing was axially in front of the front bearing pad row, and this is the area where slight silver transfer is seen on the cartridge. In general, the bearings were in very good condition.

The turbine-end hydrostatic cartridge, on the left side of Fig. 53, showed little evidence of wear. Small, dark spots on the chrome surface indicated an etching or discoloration caused by the orifice jet on the cartridge surface. Two scratch-like circumferential lines were evident on the outside-flow edge location of each pad row. The bearings showed scratch-like deformations over the circumference at each outside edge of each pad row, indicating some small degree of contamination may have occurred during operation, as can be seen in Fig. 55. Outboard of these lines were indications of discoloration or tarnish of the silver surface. The general look of the bearing would indicate very little rubbing has occurred. It should be noted that little rotative speed was developed on the turbine-end bearing cartridge during testing.

Inspection of the ball bearings was done individually and in detail. The bearings are designated No. 1 through 4, from the pump end to the turbine end. The bearings were first examined intact and then separated, with the inner races chilled to avoid damage. The two pump-end bearings (No. 1 front and No. 2 aft) appeared to be in excellent condition; each bearing rolled smoothly and showed no sign or feel of roughness of wear. The turbine-end ball bearings (No. 3 front and No. 4 aft) are also in good condition although they saw much more rotation than the pump-end ball bearings because the turbine cartridge rotated very little in the 1260 seconds of total shaft rotation as previously stated. The No. 3 bearings show signs of fairly high loads, which is indicative of the results of the high-pressure orifice of the balance piston rubbing and causing the axial thrust to be shared with the No. 3 bearing (Fig. 56). The individual ball bearings were detail inspected, and the results are as follows:

<u>No. 1 Bearing - Pump End.</u>

<u>Inner Raceway</u>. A dark gray, uniform, eccentric load path of moderate width was observed. The raceway surface was fair and smooth with some scattered pitting in the normal contact area. A few light brinnelling marks were seen at the low shoulder due to dismantling.

<u>Outer Raceway</u>. A similar, but concentric and slightly frosted raceway was observed. Light rubbing marks on the OD and cage interface area were noted. No preload spring marks were visible.

<u>Cage</u>. The surface of the cage had a fuzzy appearance with heavy rubbing at the outside diameter. There was no evidence of delamination. Ball contact rubbing at the cage pocket was moderate, but in the circumferential direction only. This indicates very low pressure drop axially across the bearings.

<u>Balls</u>. The ball surface was bright and smooth with no surface damage and little burnishing.

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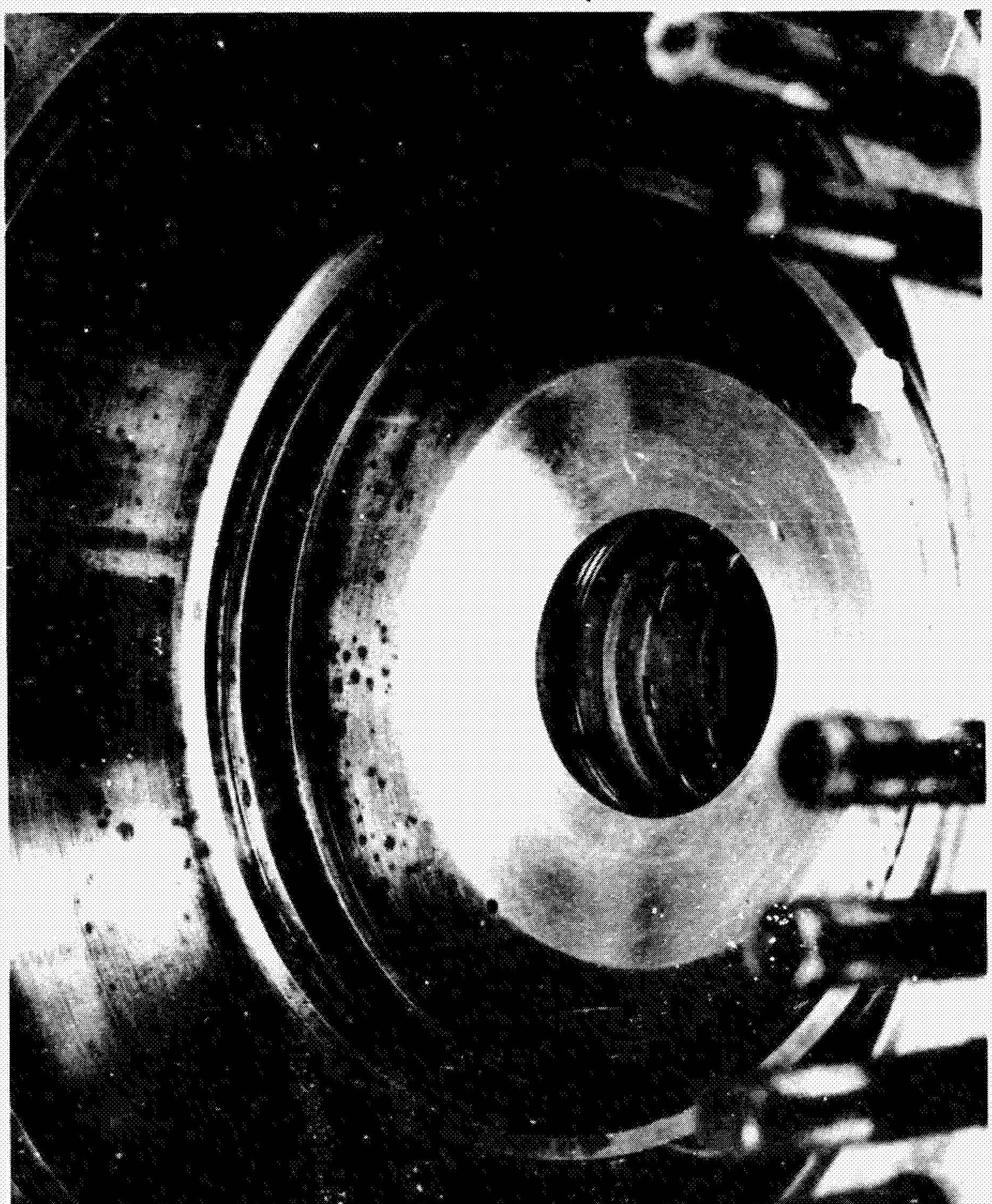

1XZ95-8/10/82-CIH*

Figure 55. Turbine-End Hydrostatic Bearing After Test

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Figure 56. Turbine-end Ball Bearing #3 After Tests

No. 2 Bearing - Pump End

Inner Raceway. A gray, wide, eccentric load path was evident with some pitting in the load path. The load path was high, consistent with the preload, but marginally below the high shoulder.

Outer Raceway. A light gray, concentric and smooth load path was observed with light rubbing marks on the OD, but no scoring. Light preload spring marks indicate sustained preload.

Cage. The surface was fuzzy with a heavy rub on the OD and no delamination. Moderate circumferential pocket contact was evident, indicating low pressure drop across the bearings.

Balls. The balls were dark gray, smooth, with no surface damage and no definite tracks.

No. 3 Bearing - Turbine End

Inner Raceway. A gray, wide, slightly eccentric track was observed that was smooth. The track runs near the high shoulder edge, indicating high loads, but is marginally below the shoulder. A rust stain was located beyond the low shoulder away from the load track, and was probably due to moisture between tests and warm-up prior to vacuum drying.

Outer Raceway. A wide but normal track contact angle was evident with smooth, gray concentric position. There were light rub marks on the OD and preload spring marks but without scoring.

Cage. Heavy rub marks on the OD were seen and moderate to heavy pocket contact circumferentially. A fuzzy cage surface was observed but no delamination.

Balls. The balls were dull, gray, and smooth with no banding and no obvious wear.

No. 4 Bearing - Turbine End

Inner Raceway. A nearly concentric, wide, uniform contact path was observed with high shoulder contact, but marginally below the shoulder. No ridges were indicated at the shoulder high point to indicate high loads at the shoulder.

Outer Raceway. A concentric, gray, uniform and smooth contact path was observed with light OD rubbing and preload spring contact marks.

Cage. A fuzzy cage with no delamination was seen with heavy rubbing on the OD. Moderate pocket contact wear was seen, indicating low pressure drop across their bearings.

Balls. A gray, uniform, and smooth surface was evident with no banding or sign of wear.

The conclusions from the bearing observations was that the bearings came through the test in good condition. An even, high preload thrust was sustained on all the bearings of 490 to 580 N (110 to 130 pounds). There was some evidence of synchronous radial load due to the eccentric load path of No. 1 and 2 bearing inner races. The outer races had some slight, occasional rotation inside the cartridges, as evidenced by the rub marks. Despite the fuzzy cage surfaces and heavy rubbing between the cage and the outer race, there was no delamination or excessive wear. The cage pocket wear indications are that little pressure drop occurred across any of the bearings. Also, the rust in the No. 3 bearing was a surface stain only, and was probably due to posttest condensation. It did not occur on the bearing race path. In general, the ball bearings were in very good condition on both bearing packages where the cartridges and balls rotated with the shaft and where the cartridges did not turn and the balls acted as a conventional bearing.

The removal of the shaft and bearings from the turbopump left the impeller stages stacked within the inlet, diffusers, and turbine housing all connected with pilot fits (Fig. 1). The inlet housing was removed from the assembly, using jacking screws, and inspected. The inducer tunnel and blade tips were free from evidence of rubbing. However, extensive damage had occured to the first-stage impeller front shroud wear rings on the inlet housing (Fig. 57). This was typical of all the other labyrinth seals on the rotor assembly. The damage is limited to the silver plating of the lands and is evidently due to excessive shaft radial motion. The damage also indicates the shaft operated axially closer to the pump end than in previous testing. The land damage was excessive enough so that stripping and replating of the silver will be required to refurbish the land. The impeller labyrinth teeth showed no evidence of damage, except for a slight roughened condition on the edges of the teeth. Removal of the first-stage impeller revealed similar damage to the impeller rear shroud labyrinth seal. The seal surface was grooved from the impeller labyrinth teeth, cutting radially into them. The silver was then swaged in between the impeller labyrinth teeth while maintaining a bond, and probably maintaining a relatively good seal. When the impeller and housing are separated, an interference exists and the silver rolled into the clearance is drawn out on disassembly by the larger diameter impeller labyrinth teeth. This condition existed on all labyrinth seals on the rotor assembly, with the silver plating damage extensive but no appreciable impeller labyrinth teeth damage. The housings were mounted on a profilometer machine, and the profiles of the seal lands recorded. The results indicate a radial movement of the rotor causing wear into the land at least 0.25 mm (0.010 inch) deep on all seals. This is combined with a measured labyrinth seal diametral clearance of 0.152 to 0.203 mm (0.006 to 0.008 inch). This damage verifies the dynamics data which reported high shaft radial motions during the testing. This damage is discussed further in the Dynamics Analysis section of the report.

The turbine housing contains the silver-plated ID land of the balance piston high-pressure orifice (Fig. 55). A rubber mold of this surface indicates the outside diameter land of the high pressure orifice (which is located on the impeller tip) slightly rubbed the silver plating. This rub created approximately 0.076 mm (0.003 inch) radial material removal at the corner reducing to zero material a distance of approximately 0.203 mm (0.008 inch) forward of the corner. This is shown in Fig. 58.

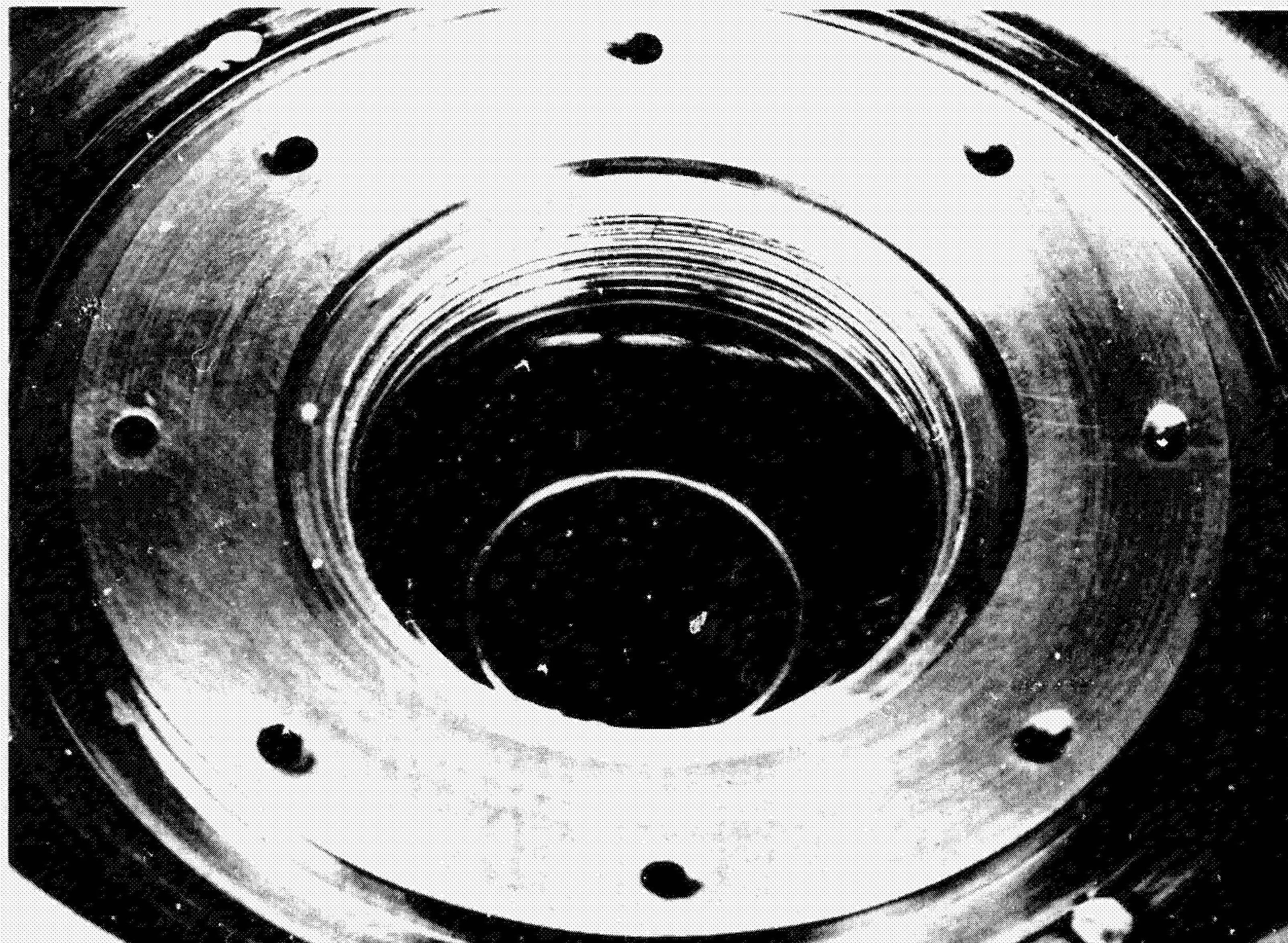

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Figure 57. Pump Inlet Housing - Front Labyrinth Seal Damage

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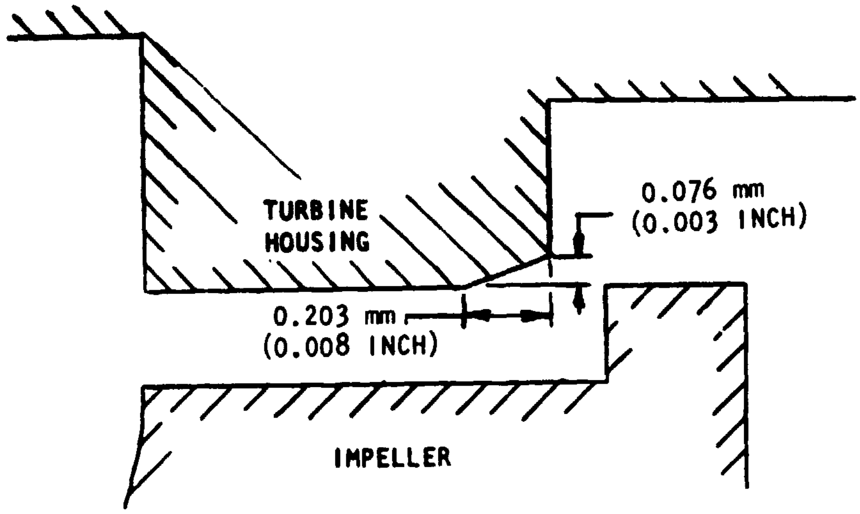

Figure 58. Balance Piston High-Pressure Orifice Damage Schematic

This wear pattern confirms the analysis during testing that the axial position of the shaft was operating further toward the pump end than previously expected. This damage occurred because of the relaxed radial clearance allowed by the hydrostatic bearing. This was coupled with allowing the high-pressure orifice corner of the impeller to move forward past the orifice corner of the housing by relaxing the forward stop position of the turbine-end cartridge during buildup. Inspection of the low-pressure rub ring indicated very little contact wear, also indicating the aft turbine end cartridge-bearing stop was effective.

The disassembly and inspection of the turbopump was completed and photographs of the hardware were taken to document their condition. The major damage to the turbopump was caused by the high radial shaft movements encountered at high speeds. These conditions will be fully explored in the Dynamic Analysis section later in this section. The damage repair requirements to the hardware consist mainly of stripping and replating of the silver labyrinth seals and balance piston high-pressure orifice surfaces followed by remachining to dimensional requirements. Replating of the copper for the turbine tip and interstage seals also will be required.

PERFORMANCE ANALYSIS, PREDICTION, AND EMPIRICAL RESULTS

A complete performance analysis of the turbopump was required before the selection of the hydrostatic bearing operating clearances, orifice sizes, and operating supply pressures could be determined. The analysis started with the determination of the hydrostatic bearing performance parameters including direct and cross-coupled stiffness and damping coefficients and flowrate. These were calculated for given clearances over the turbopump operating speed spectrum and at various supply pressure levels. These studies provided the dynamic coefficients for the hydrostatic bearing which were then coupled with the duplex pair of ball bearings and input into the rotordynamic analytical model for determination of critical speed, stability, and dynamic response for each operating condition analyzed. This analysis was done for several operating clearances and operating supply pressure characteristics. The results provided the information for sizing the bearing clearances and orifice diameter and characterized the effects of supply pressures on the rotordynamics of the turbopump. Once selection of the dimensional parameters was completed, additional care was taken to find acceptable operating conditions based on the rotordynamic analysis.

The hydrodynamic analysis of the hydrostatic bearings began early in the program. The major requirements of the analysis was the need to accurately predict the hybrid hydrostatic bearing performance capabilities including direct and cross-coupled stiffness and damping so that the data could be used to determine the rotordynamics of the turbopump operation and the hydrostatic bearing required flowrates. As the analysis progressed, it was found that using the internally available supply flow and pressures from the turbopump complicates the rotordynamic conditions of the turbopump at the high speeds. This is caused by the fact that as bearing stiffness increases with the increase in hydrostatic bearing supply pressure at increased speed, the rotor natural frequencies also increase. This can cause a tracking phenomenon that allows the critical speed to rise with the shaft speed. This condition is serious if the rotor natural frequency with speed matches closely the shaft speed over a wide speed range. However, this can also be a beneficial condition if the natural frequency does not match the shaft speed but runs parallel to it.

Another problem of concern is the operation of the hydrostatic bearing over the pressure range that will encompass the two-phase region of the pressure and temperature. When this occurs, the fluid densities change rapidly as the fluid pressures drop in their path through the hydrostatic bearing orifice and fluid film. This density change can also bring about choking in the fluid film which decreases the actual flowrate and increases the pressure differential across the fluid film.

The analysis of the hydrostatic bearings as it applies to turbopump operation will be discussed in this section. The rotordynamic analysis results, which were necessary to define acceptable operating conditions for the turbopump testing, will be described. These studies evaluated a series of five possible operating conditions on the turbopump in an effort to determine the effects of clearances and bearing supply pressure variations on the rotordynamic characteristics of the turbopump. Also discussed will be the analysis and results of the hybrid bearing testing. These results will be presented with evaluations and conclusions about the operational characteristics and capabilities of a hybrid bearing system within a turbopump.

Hydrostatic Bearing Analysis

The tools available for the hydrostatic bearing analysis consisted of a computer code developed at Rocketdyne to predict the hydrodynamic characteristics of the hydrostatic bearing. The code analysis is based on finite difference methodology and has both design and analysis capability. The code has been developed over several years and has been used in the design of squeeze film dampers, hydrostatic seals, and shrouded axial flow pumps for damping characteristics. The capabilities of the code includes the following:

- Direct and cross-coupled spring rate and damping coefficients
- Flow in each pocket and total flow
- Pressure distribution and resultant force
- Attitude angle due to rotation
- Clearance distribution
- With and without rotation
- Turbulent effects included
- Inertia force effects included
- One- or two-pad rows having a total maximum of 20 pockets
- Exccentricity up to 0.8
- Symmetrical or unsymmetrical sump pressure distribution
- Checks pneumat. hammer stability
- Design of orifice restrictor

The limitations of the code are as follows:

- No angular misalignment capability
- No two-phase flow capability without outside iterations
- No power consumption calculations except for fluid torque and flowrate
- Uniform clearances along axis; no taper

The computer code was checked at the start of the analysis with the small amount of available data and independent analysis. The first test was a comparison with the predictions published in the MTI report (Ref. 2). The comparisons of MTI predictions with Rocketdyne predictions using the same baseline designs and operating conditions showed good agreement for predicted flowrate and direct stiffness values. Values of Rocketdyne predicted flowrate from duplicating NASA-LeRC test data also agreed within 15%. Initial analysis of the turbopump hydrostatic bearing system entailed definition of the specific operating conditions of the turbopump and available hydrostatic bearing supply flows.

Static pressure and temperature distributions were used to find a suitable source for the internal tapoff flow supply for the bearings. These data are given in Fig. 59 and 60 for the design speed, and are taken from previous test data. The high pressure levels in the rear bearing cavity area dictate the flow must be taken from the pump discharge line for the rear hydrostatic bearing supply. This supply pressure is more than sufficient to supply the front bearings, but the temperature of the flow is also high due to the heating associated with the pressure rise. The inlet pressure and pump bearing sump pressure is approximately 38 to 65 N/cm^2 (55 to 95 psia) (well below the critical pressure of 129 N/cm^2 (187 psia) for the hydrogen vapor dome). The thermodynamic process of this flow path is given in Fig. 61. To minimize the choking effect of the hybrid bearing flow due to density change with pressure, the isenthalpic pressure drop analysis was made, outside the computer code, using the three diffuser discharge stage state conditions for the supply fluid. The state points at the sump pressures were then calculated. These data are shown in Table 6. The analysis assumes no frictional heating effects. The results show that the tapoff from the first-stage diffuser discharge results in the lowest internal energy, highest density fluid available, using a pump fed source.

The major concern was that if choking occurred, it would be located at the exit of the pump-end hybrid bearing. This, in turn, would limit the stiffness of the hydrostatic film. This would be caused by the limit of the pressure level above the sump pressure at which choking occurred. Frictional heating effects in the fluid film when accounted for would result in a slightly higher pressure limit for the effective sump pressure. The available stiffness was expected to be sufficient for satisfactory operation. The two-phase state of the fluid in the bearing cavity was not expected to cause a ball bearing problem if the balls were not rotating appreciably. The sump was to be evacuated by an overboard drain (Fig. 3) which had to be of sufficient size to handle the flow requirements. It was planned to hold the sump pressure to slightly below the inlet pressure, if possible, to eliminate or minimize the hot hydrogen flow into the pump inlet. A seal would have been appropriate for minimizing the warm fluid leakage to the inlet in an optimized configuration; however, the geometry of the turbopump left little room for incorporation of a seal.

The analysis required the definition of the pump-supplied pressure levels to the hydrostatic bearings as a function of pump speed. A review of previous test data (Ref. 1) provided the available supply manifold pressures for the respective pump-end and turbine-end bearings. These data are given in Fig. 62 and 63, respectively. Also shown is the estimated pad and sump pressures of the bearings.

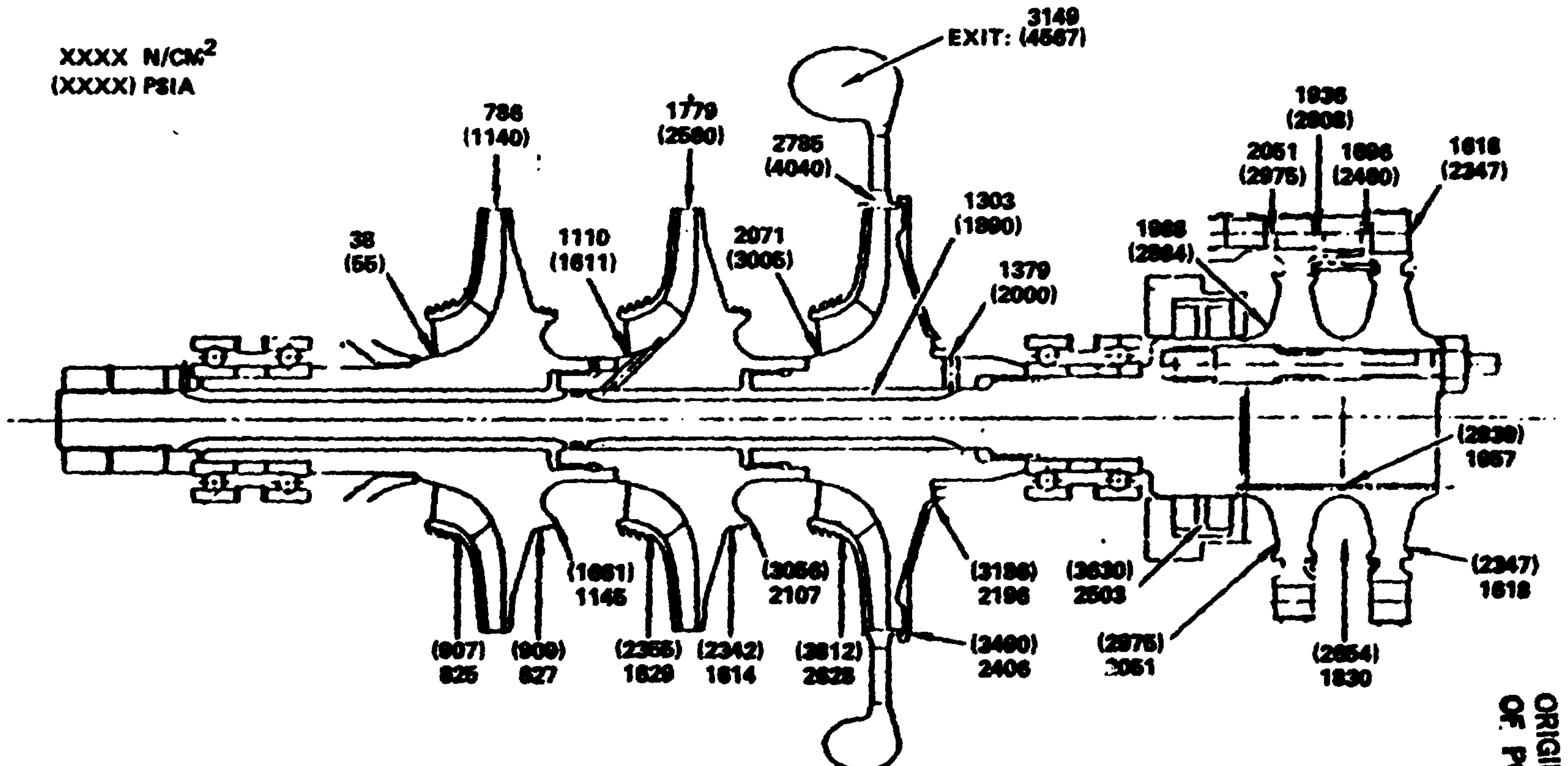

Figure 59. Mark 48 Fuel Turbopump Static Pressures at 95,000 rpm, 9950 rad/s

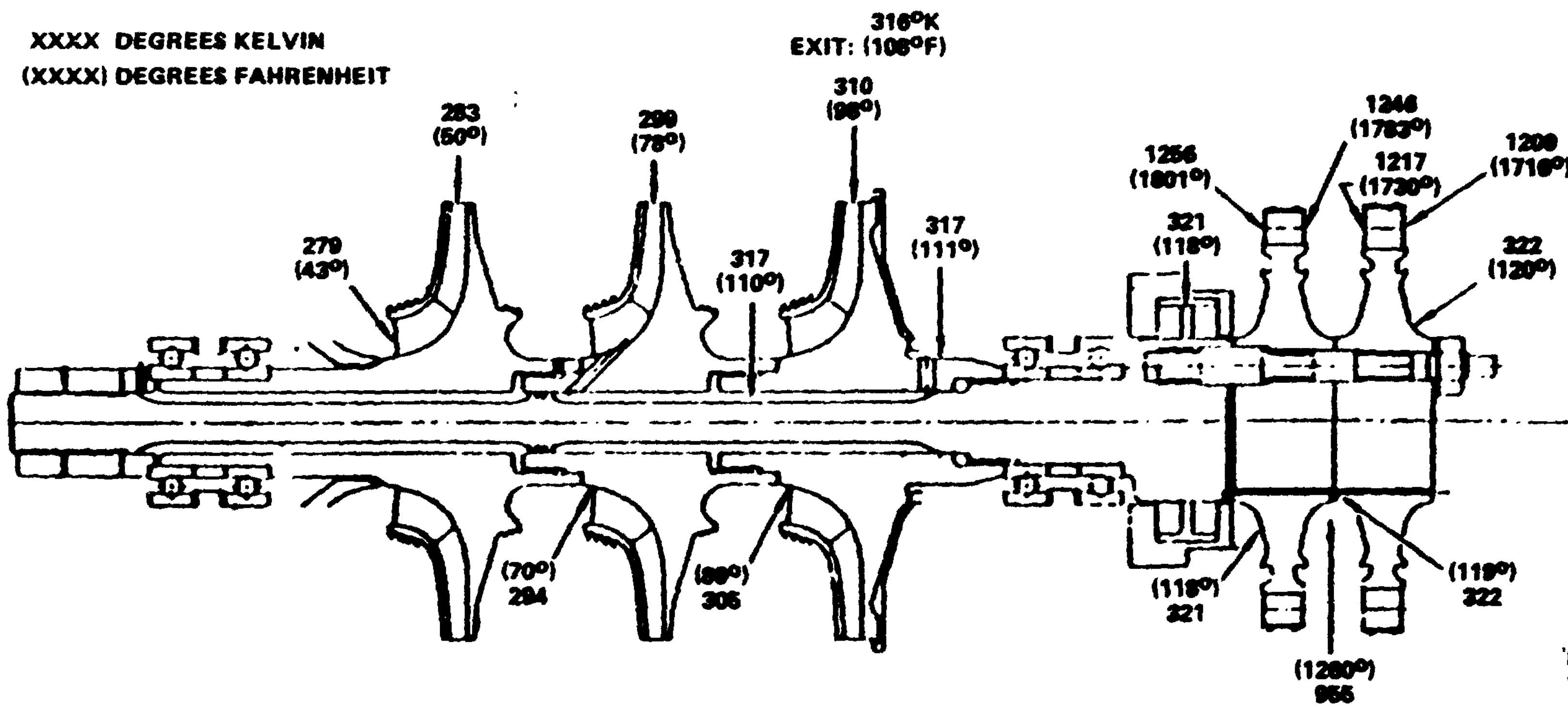

Figure 60. Mark 48 Fuel Turbopump Fluid Static Temperatures at 95,000 rpm, 9950 rad/s

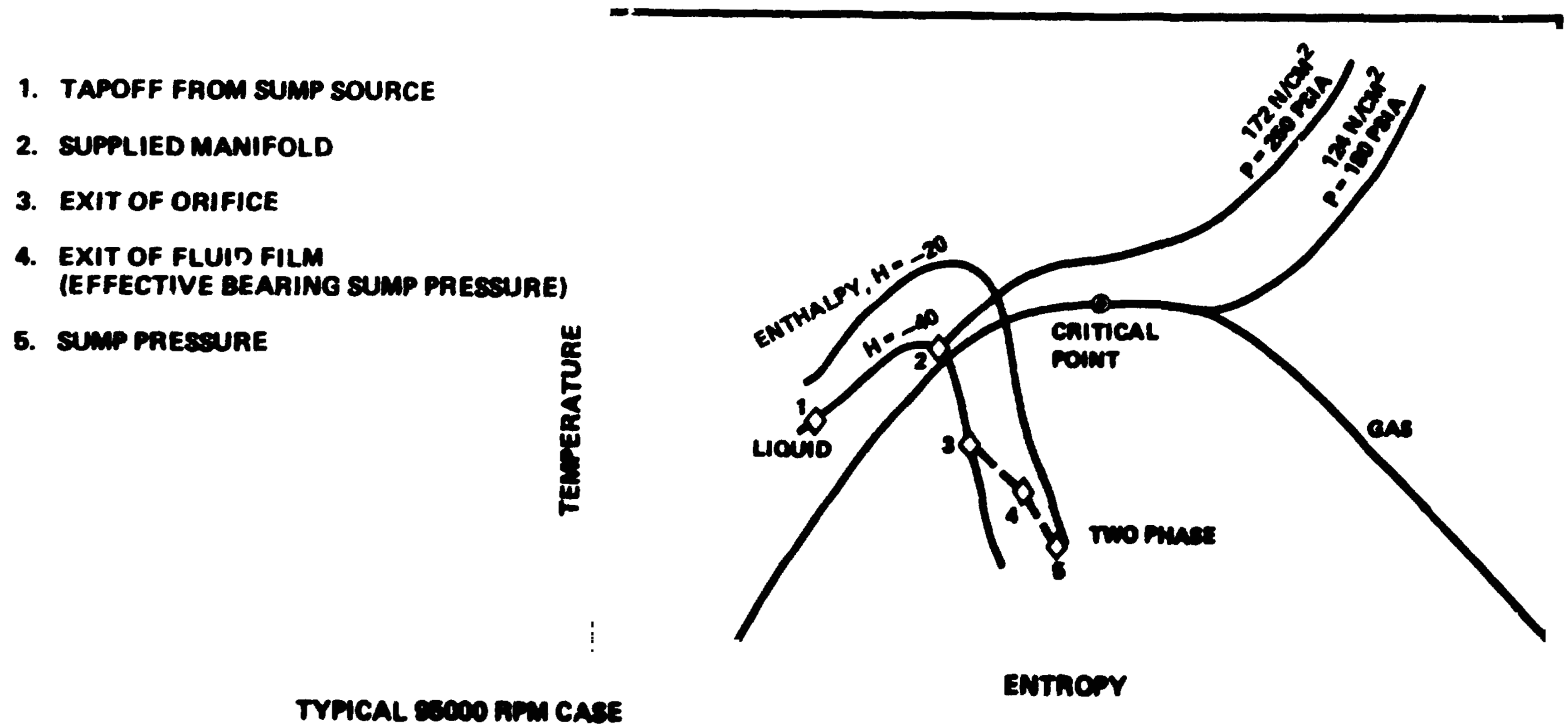

Figure 61. Thermodynamic Processes Hybrid Bearing Flow

TABLE 6. STATE CONDITIONS OF HYDROGEN FROM INTERNAL SOURCE AT 95,000 RPM

TAPOFF LOCATION	DIFFUSER FIRST STAGE	DIFFUSER SECOND STAGE	DIFFUSER THIRD STAGE
IMPELLER PRESSURE, PSIA (N/CM^2)	1140 (786)	2580 (1779)	4040 (2786)
DIFFUSER PRESSURE, PSIA (N/CM^2)	1523 (1050)	2950 (2034)	4415 (3044)
TEMPERATURE, R (K)	50 (28)	78 (43)	98 (54)
ENTHALPY, BTU/LB (JOULE/KG)	-36.0 (-8546)	+74.6 (+17709)	+167.2 (+39690)
DENSITY, LB/FT^3 (KG/M^3)	4.49 (71.9)	4.33 (69.4)	4.30 (68.9)
HYBRID BEARING SUMP			
PRESSURE, PSIA (N/CM^2)	55 (38)	55 (38)	55 (38)
TEMPERATURE, R (K)	46.1 (26)	46.1 (26)	72.3 (26)
ENTHALPY, BTU/LB (JOULE/KG)	-36.0 (-8546)	+74.6 (+17709)	+167.2 (+39690)
DENSITY, LB/FT^3 (KG/M^3)	0.890 (14.3)	0.311 (4.98)	0.152 (2.43)
DENSITY RATIO	5.0	13.9	28.3

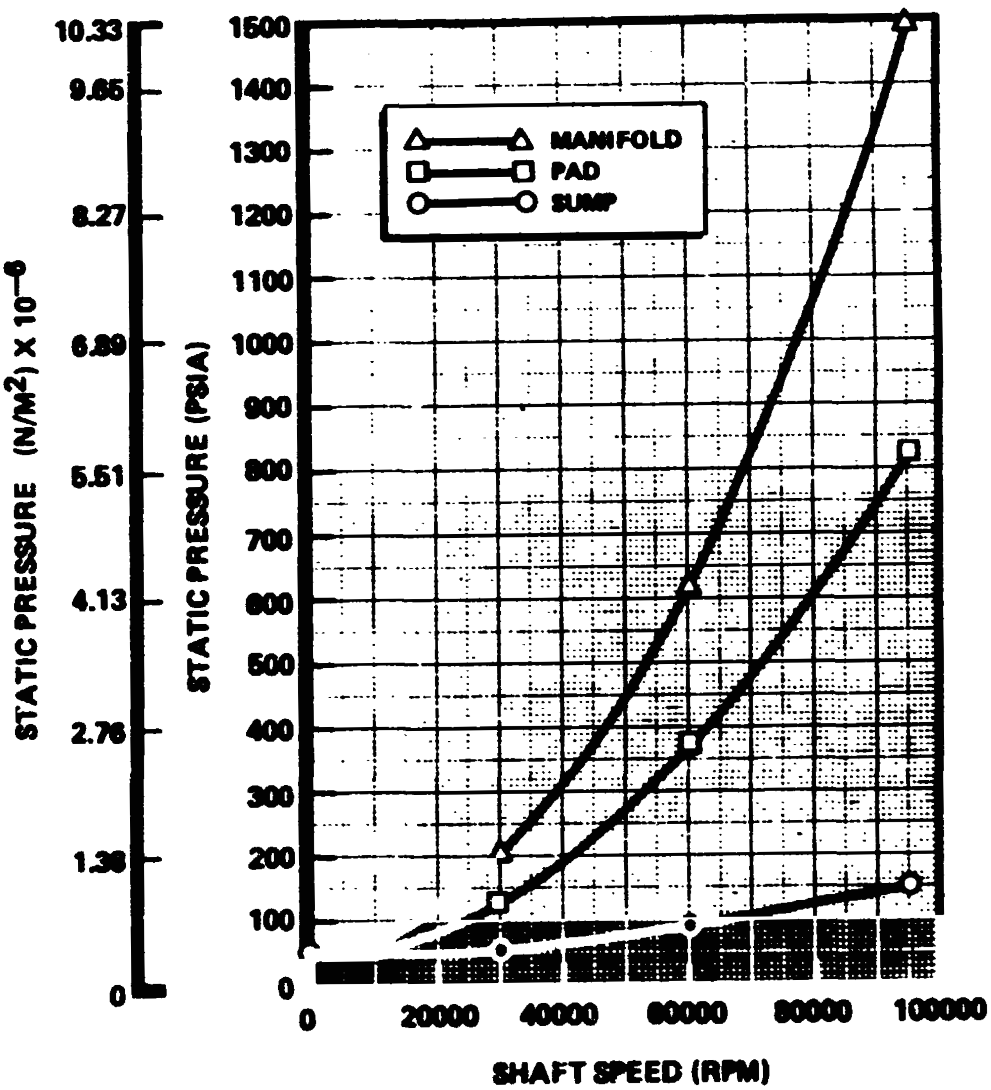

Figure 62. Hybrid Bearing Pressure Distribution - Pump Bearing

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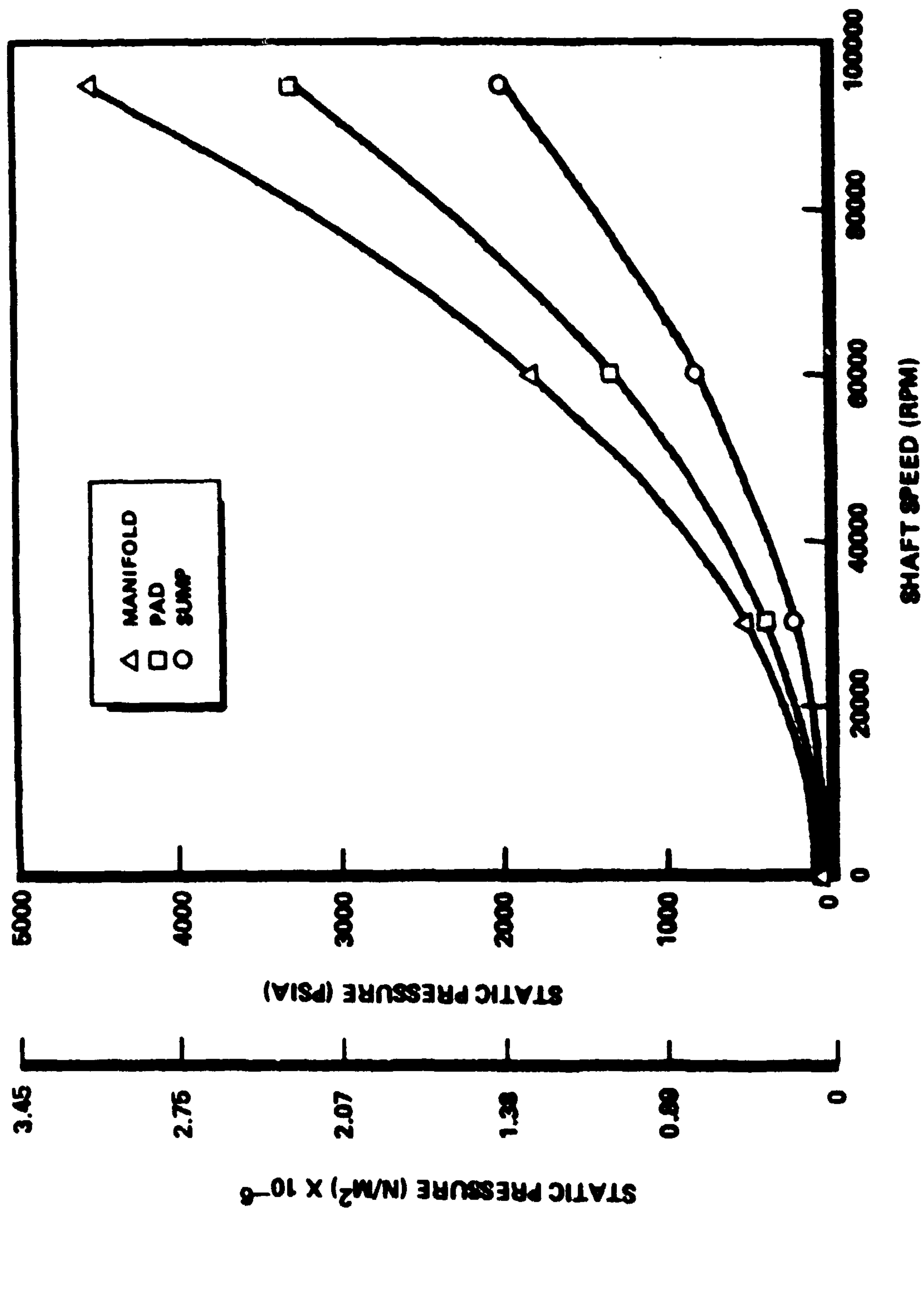

Figure 63. Hybrid Bearing Pressure Distribution - Turbine Bearing

The preliminary hydrodynamic analysis and performance predictions for the hydrostatic bearing was developed for a minimum operating radial clearnce of 0.0305 mm (0.0012 inch) on both pump and turbine end bearings. This condition is referred to as Case A in the analysis. The stress analysis had defined the radial operating clearance conditions for the respective bearing as a function of journal speed in Fig. 8 and 9. An additional case for the maximum radial clearance at operating conditions of 0.0457 mm (0.0018 inch) also was analyzed and was identified as Case B. This maximum and minimum radial clearance formed the expected tolerance band of possible operating conditions, including possible variations in the structural calculations and fabrication tolerance capabilities.

The hydrodynamic analysis of the final design configuration resulted in the following predictions for the operating conditions. The predicted flowrate for each bearing is given in Fig. 64 for each bearing at maximum and minimum clearance conditions. Similar results are presented in Fig. 65 through 68 for the predicted direct and cross-coupled values of stiffness and damping. The results were developed for the pump end bearing, using the internal supply pressures tapped off from the first-stage crossover and for the turbine end bearing, using the pump discharge pressures. It is interesting to note that the direct stiffness values decrease by nearly a factor of 5 over the 0.0152 mm (0.0006 inch) clearance range used.

Rotordynamic Design Considerations

Case A and Case B - Clearance Effects. The results of the rotordyanmic analysis that follows dictated that several cases of operational conditions for the hydrostatic bearing supply pressure levels be analytically determined. The rotordynamic model was developed and the analysis of the rotordynamics of Case A and Case B was completed for the range of predicted hybrid bearing performance parameters presented as a function of speed. The results of the dynamic analysis are given in Fig. 69 and 70 and Table 7. The data presented in Table 7 indicate the critical speeds that occur and include the results of a dynamic analysis with the hydrostatic only (no ball) configuration. The critical speed is defined as the speed at which the rotor natural frequency of Fig. 69 and 70 (solid lines) intersect the shaft synchronous speed line. The comparison of the curves' possible intersections indicates that the third critical speed could vary from 5027 to 13300 radians/sec (48,000 to 127,000 rpm) over the clearances range used. Also, since the slope of the rotor natural frequency is nearly parallel to the synchronous line, the accuracy of prediction of the critical speeds in that range is very limited. This phenomenon is referred to as tracking. As a result, it was determined during the design review that further analysis and performance prediction would be completed. Increasing the maximum operating radial clearance to 0.061 mm (0.0024 inch) would reduce the stiffness further and allow the third critical speed to intersect the synchronous line at a point slightly below 5027 radians/sec (48,000 rpm) for the 0.0457 mm (0.0018 inch) clearance. The clearance increase was also expected to improve the marginal stability of the case with smaller clearance which was calculated and is indicated in Fig. 71. The previous maximum operating clearance of 0.0457 mm (0.0018 inch) would then be used as the minimum operating clearance. Two areas of major concern occur, however, with this change. One is that the clearance increase results in a large

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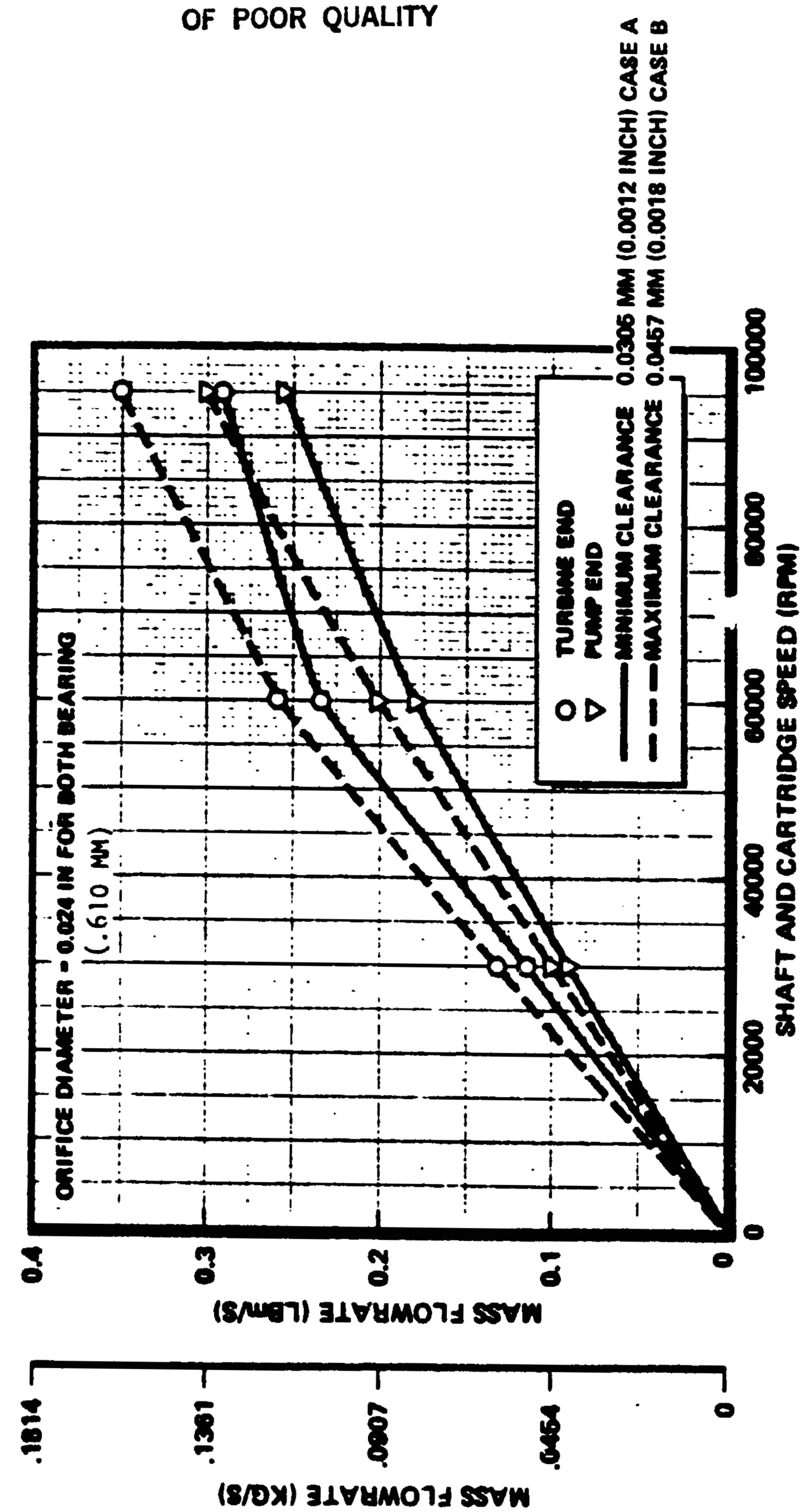

Figure 64. Predicted Hydrostatic Bearing Flowrates, Case A and B

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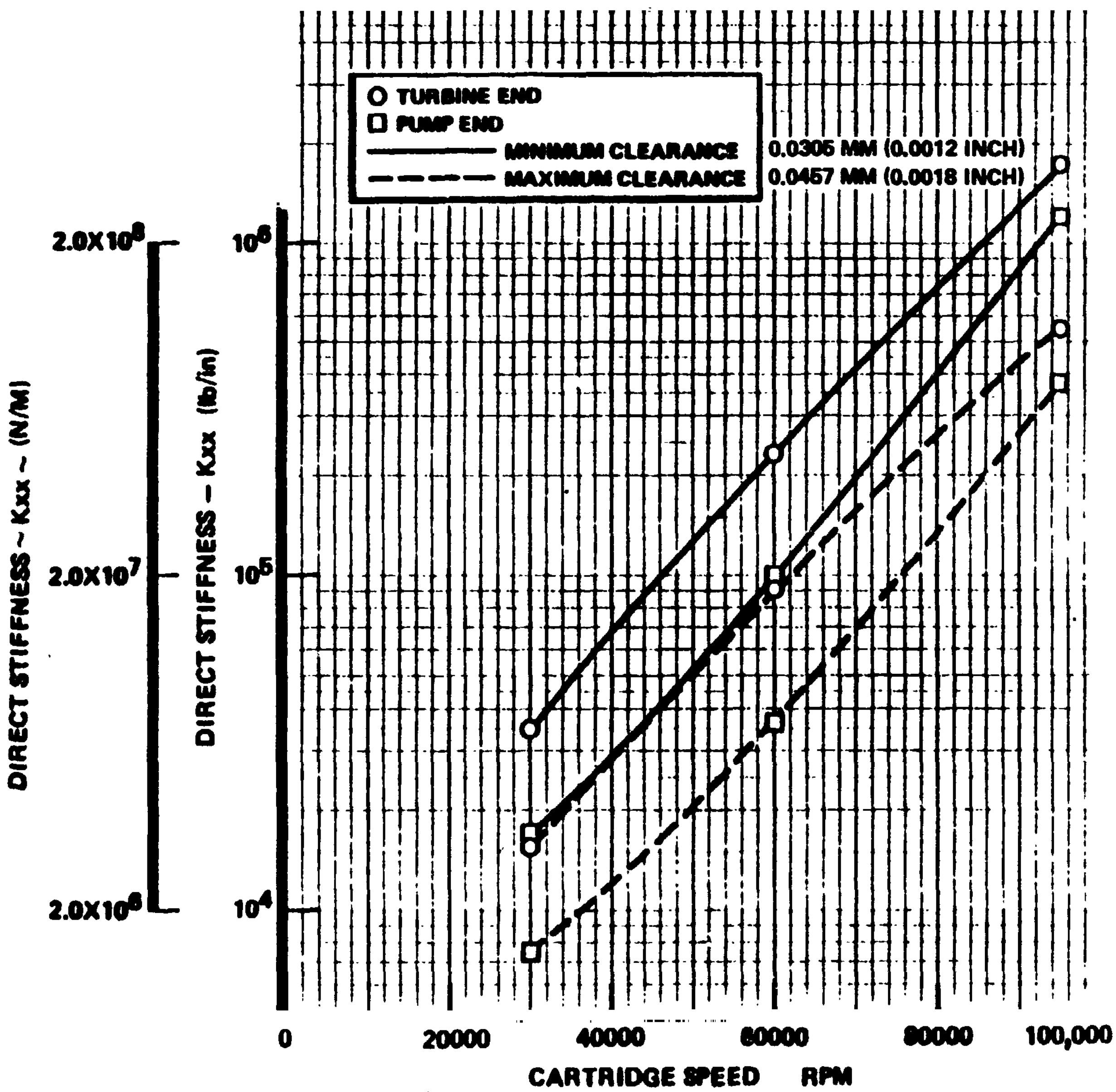

Figure 65. Predicted Hydrostatic Bearing Stiffness,
Cases A and B

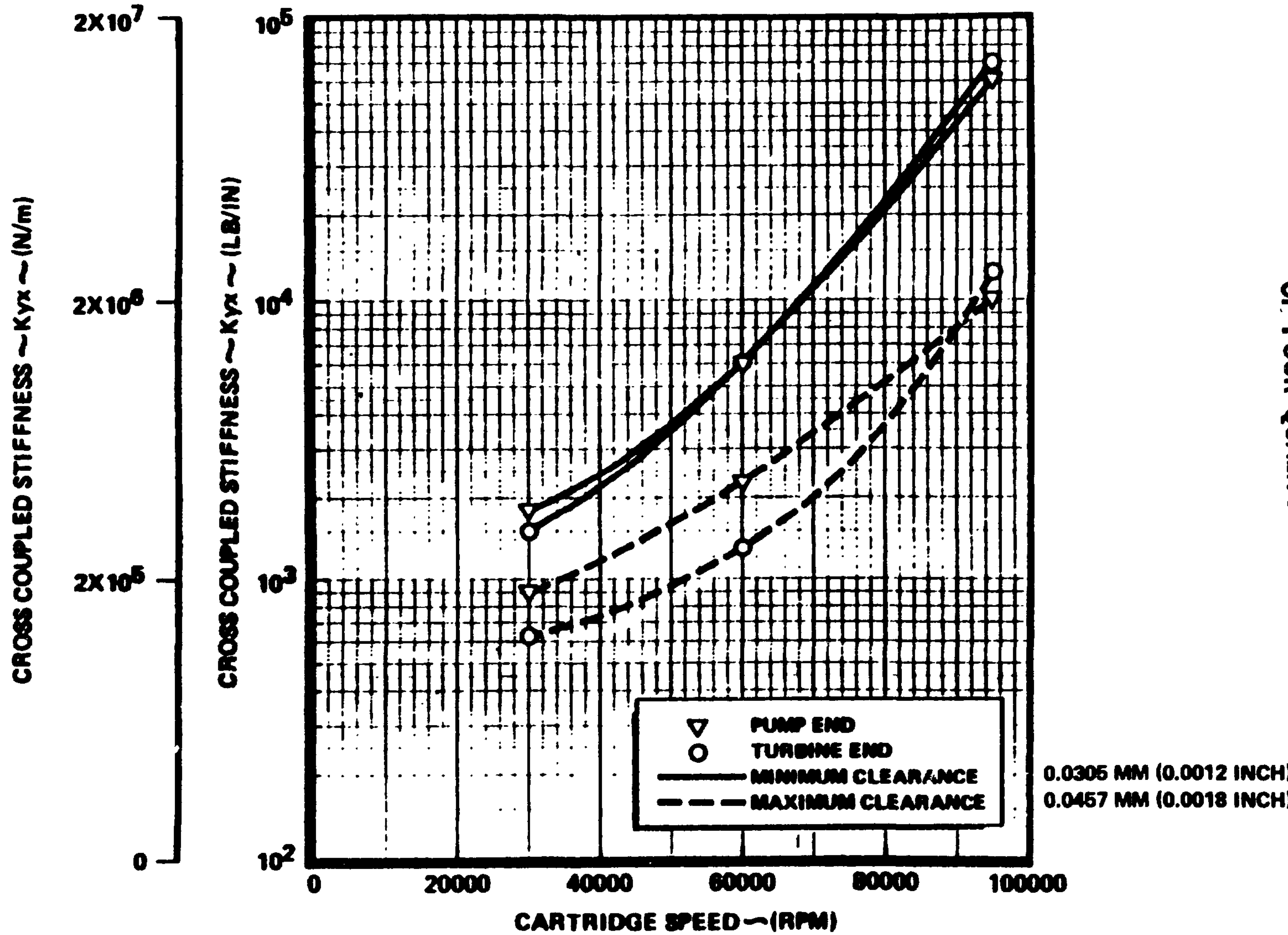

Figure 66. Predicted Hydrostatic Bearing Cross-Coupled Stiffness, Cases A and B

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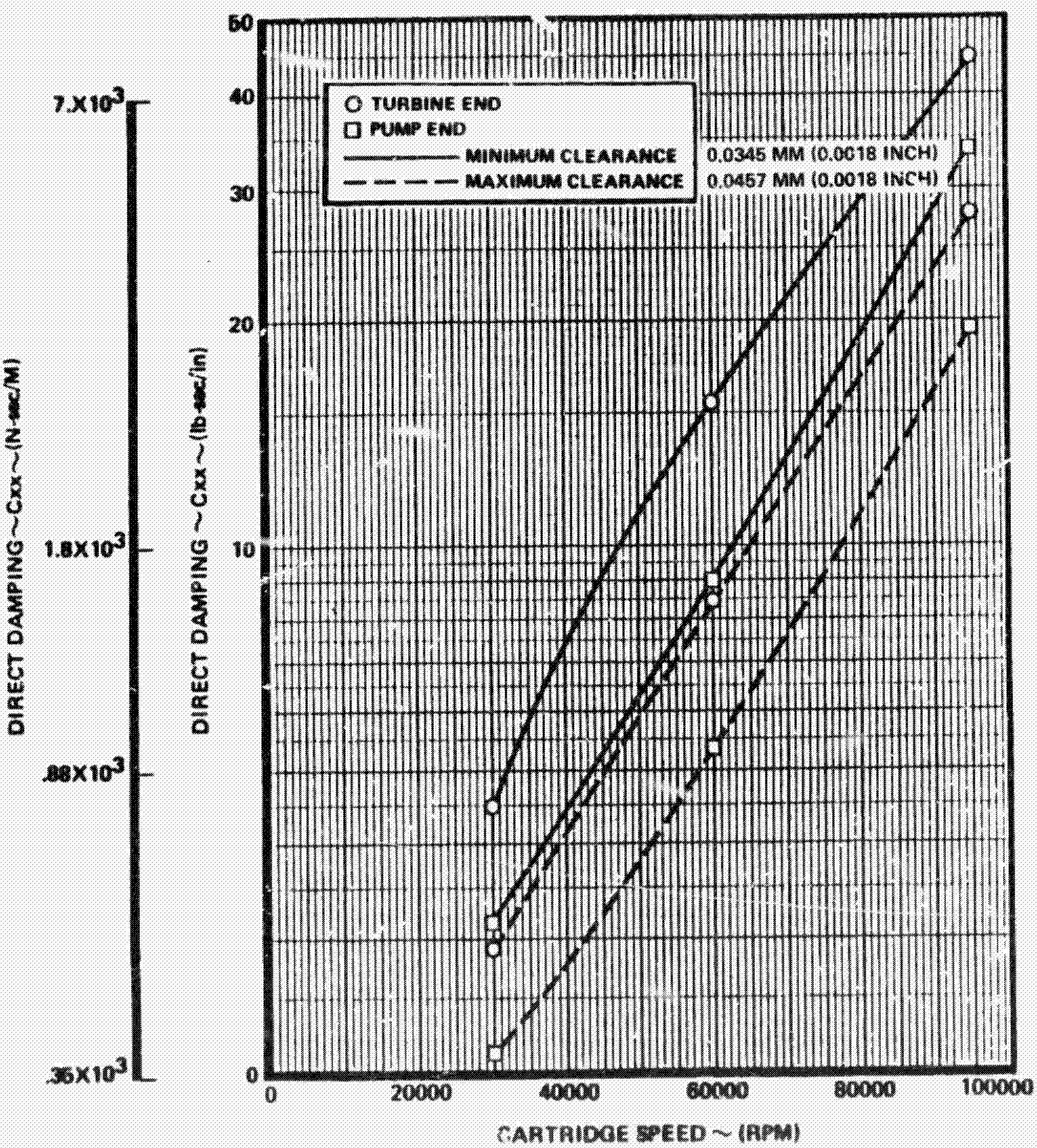

Figure 67. Predicted Hydrostatic Bearing Direct Damping, Cases A and B

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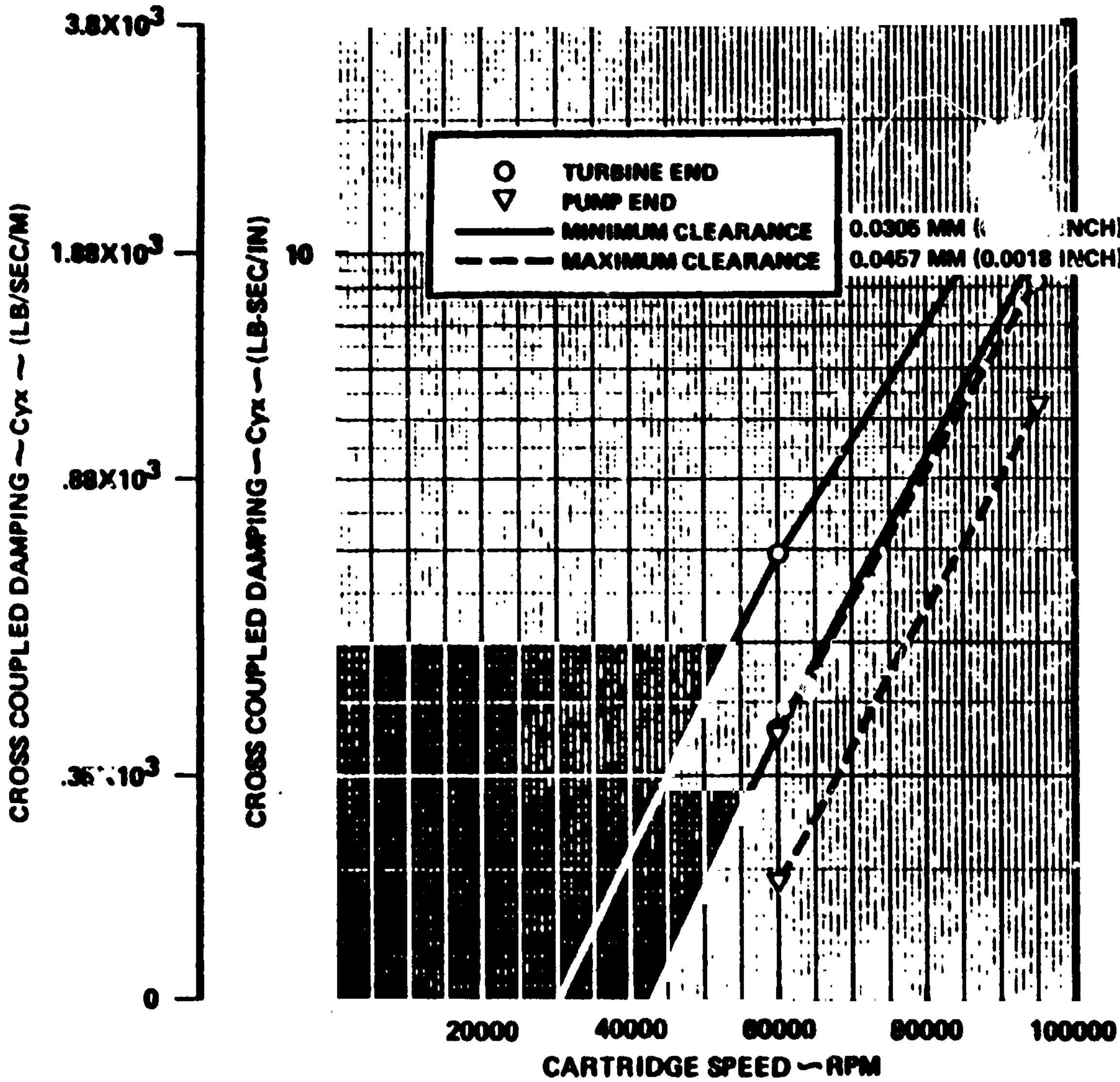

Figure 68. Predicted Hydrostatic Bearing Cross-Coupled Damping, Cases A and B

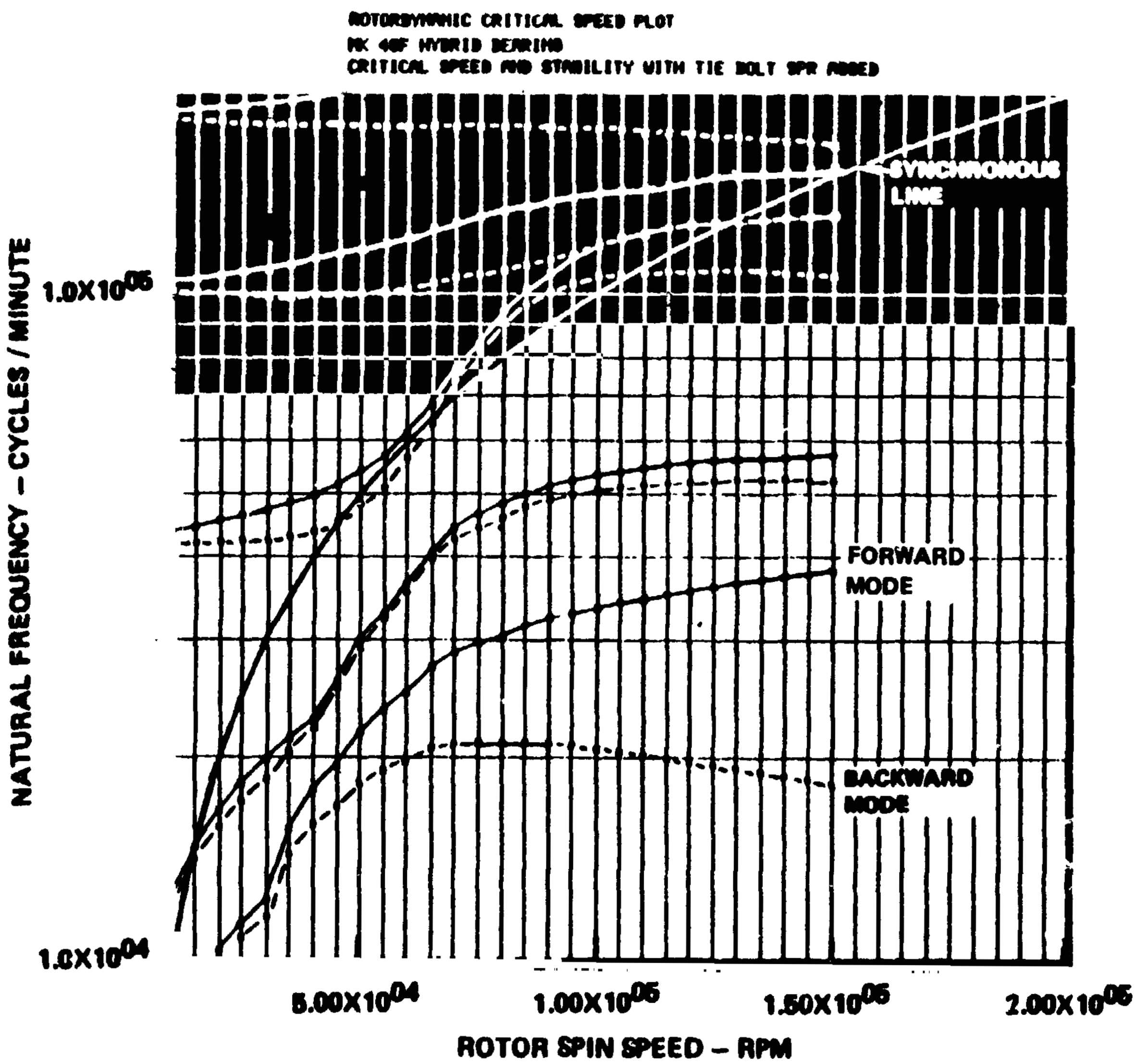

Figure 69. Turbopump Rotordynamic Characteristics - Case A; Hybrid Bearing Minimum Clearance 0.0305 mm (0.0012 inch)

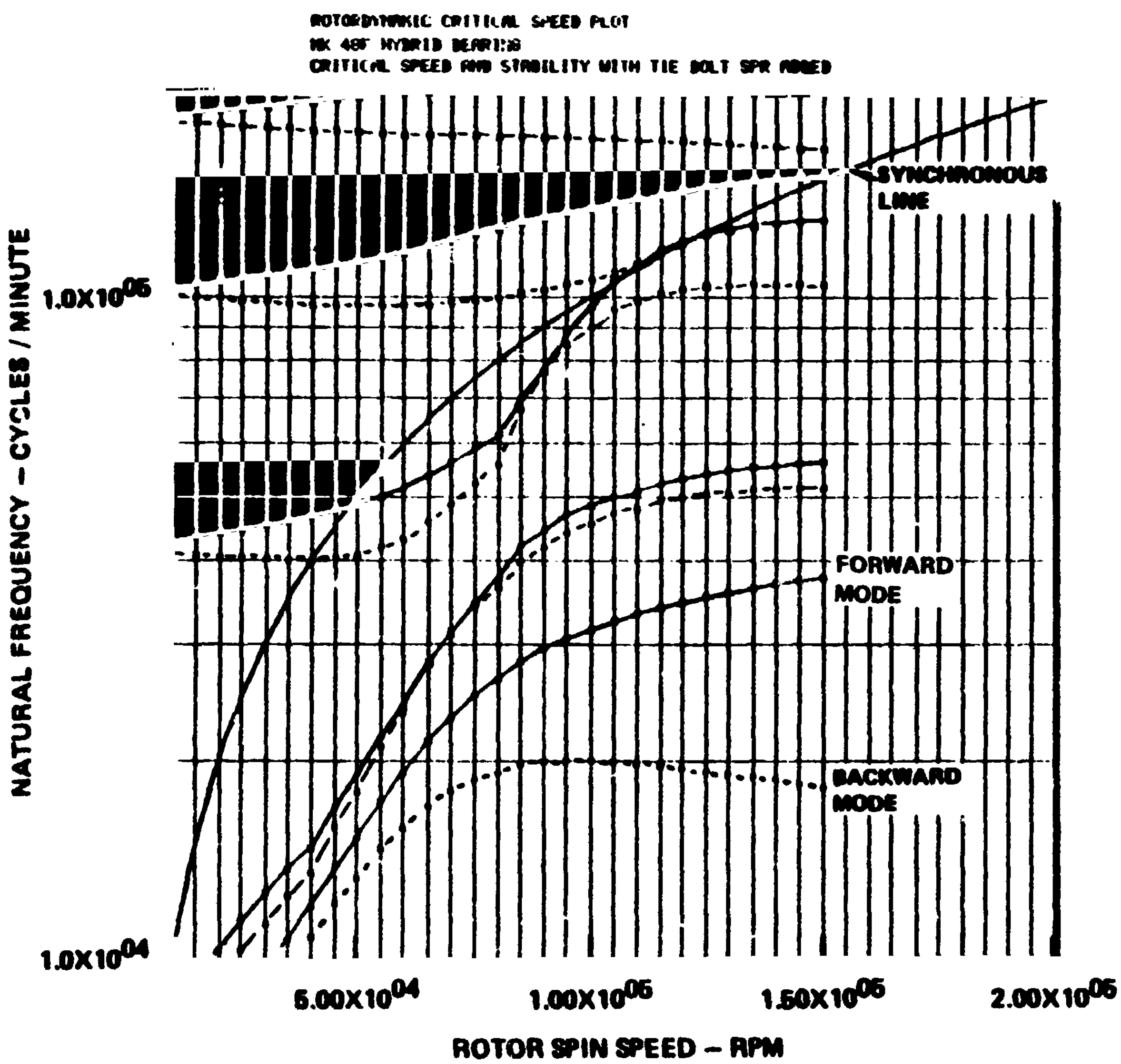

Figure 70. Turbopump Rotordynamic Characteristics - Case B; Hybrid Bearing Maximum Clearance 0.0457 mm (0.0018 inch)

TABLE 7. TURBOPUMP CRITICAL SPEEDS WITH HYBRID BEARINGS

- **ROTOR ON HYBRID BEARINGS** — **RIGID CASING**
- **NO BALL CONFIGURATION** — **RIGID CASING**

	CASE A MINIMUM BEARING CLEARANCE 0.0305 MM (0.0012 INCH)	CASE B MAXIMUM BEARING CLEARANCE 0.0457 MM (0.0018 INCH)	NO BALL CONFIGURATION	
			MIN. CLR.	MAX. CLR.
CRITICAL SPEED (RPM)	6,000	[illegible],500	7,500	5,000
	15,000	[illegible],200	32,500	25,000
	127,000	[illegible],000	>150,000	> 150,000
		1[illegible],000		

NOTE FORWARD PRECESSION MODES ONLY ARE SHOWN

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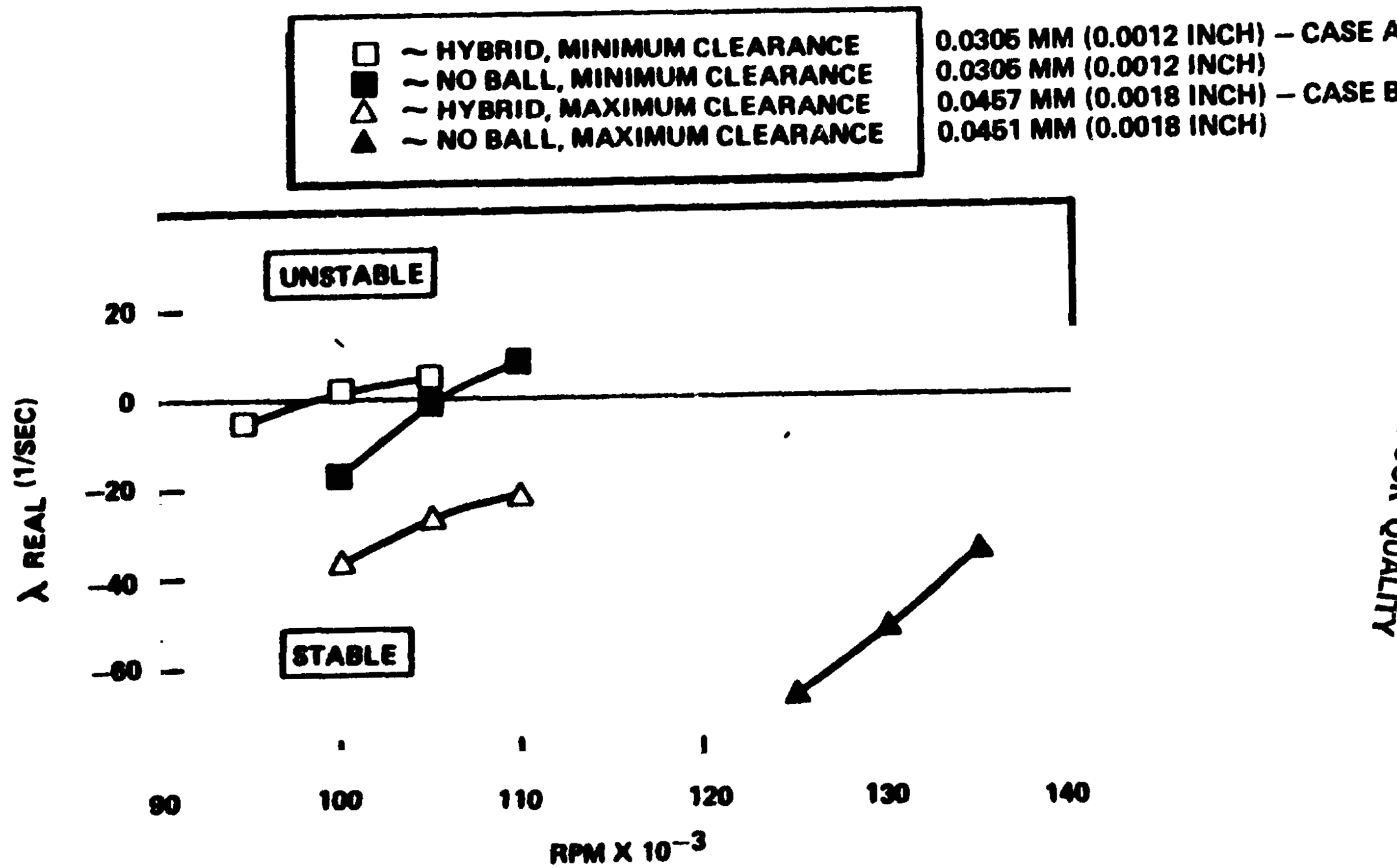

Figure 71. Mark 48-F Turbopump Stability Map

recirculation requirement. The other is that by merely changing the clearance and maintaining an orifice size constant, the fluid film pressure ratio is drastically changed. This can result in a penalty to the system where other changes, such as reduction in the supply pressure and/or orifice size, may give the same stiffness reduction with a much smaller penalty involved. Further analysis confirmed this conclusion.

Case C - Intermediate Supply Pressure Levels. Due to the critical speed tracking encountered on the preliminary analysis, it was necessary to determine methods whereby this phenomenon could be eliminated or moved outside of the operating envelope. To do this, it was necessary to review the pump internal pressure capability to determine if other supply sources might be usable and to completely define the problem. Also, the use of other clearances or orifice sizes was a feasible approach to the solution. The initial attempt to operate the hybrid bearing system was to utilize the full range of turbopump supply pressures to give a broad range of stiffness capability. That range is given in Fig. 63. A close review of these data indicates that the pump discharge pressure used for a bearing supply could be as high as 3447 N/cm^2 (5000 psi) at maximum speed with the supply pressure varying with the speed squared. A range at 9948 radians/sec (95,000 rpm) of 3102 to 1861 N/cm^2 (4500 to 2700 psi) for bearing supply pressure was considered for the turbine bearing coinciding with a balance piston (hydrostatic bearing) sump pressure of 1620 N/cm^2 (2350 psi) above inlet pressure. The pump bearing available pressure supply range was considered to be 827 to 207 N/cm^2 (1200 to 300 psi), Fig. 72. A mid-range pressure level was considered as 2482 N/cm^2 (3600 psi) for the turbine and 689 N/cm^2 (1000 psi) for the pump bearing at 9948 radians/sec (95,000 rpm) for the stiffness and damping coefficients of Case C. These were input into the rotordynamic analysis, with results of the natural response frequencies given in Fig. 73 and 74. Figure 73 presents the rotor only modes assuming a rigid casing. Figure 74 presents the rotor and casing modes using the superposition methods (developed in an earlier vibration analysis task reported in Ref. 3) and connecting the casing and rotor together with the hydrostatic and ball bearing dynamic conditions. The results clearly show that the third natural rotor response still tracks the synchronous speed frequency. This cannot be allowed since the turbopump would essentially be operating at the third critical speed anywhere above 5236 radians/sec (50,000 rpm).

Case D - Constant Supply Pressure at High Speed. In an attempt to correct the tracking condition described in Cases A, B and C, the analysis was made to determine what was required to reduce the third natural frequency to a constant. The turbopump supply pressures of Fig. 72 were used for the initial low speed segment of the start transient to 5236 and 6807 radians/sec (50,000 and 65,000 rpm) for the respective pump and turbine bearing supply pressures. Above these speeds, the supply pressure was held constant. This supply pressure distribution with speed is given in Fig. 75. It should be noted that with turbine supply pressure a constant above 6807 radians/sec (65,000 rpm), the hydrostatic bearing pressure differential decreased since the sump pressure rises to approximately 1379 N/cm^2 (2000 psi) at 9948 radians/sec (95,000 rpm) for this case. Combining this and decreasing clearance with speed, generates nearly constant stiffness and damping values. The results of the dynamic analysis using the stiffness and damping parameters from this case are indicated in Fig. 76 and 77. For the case

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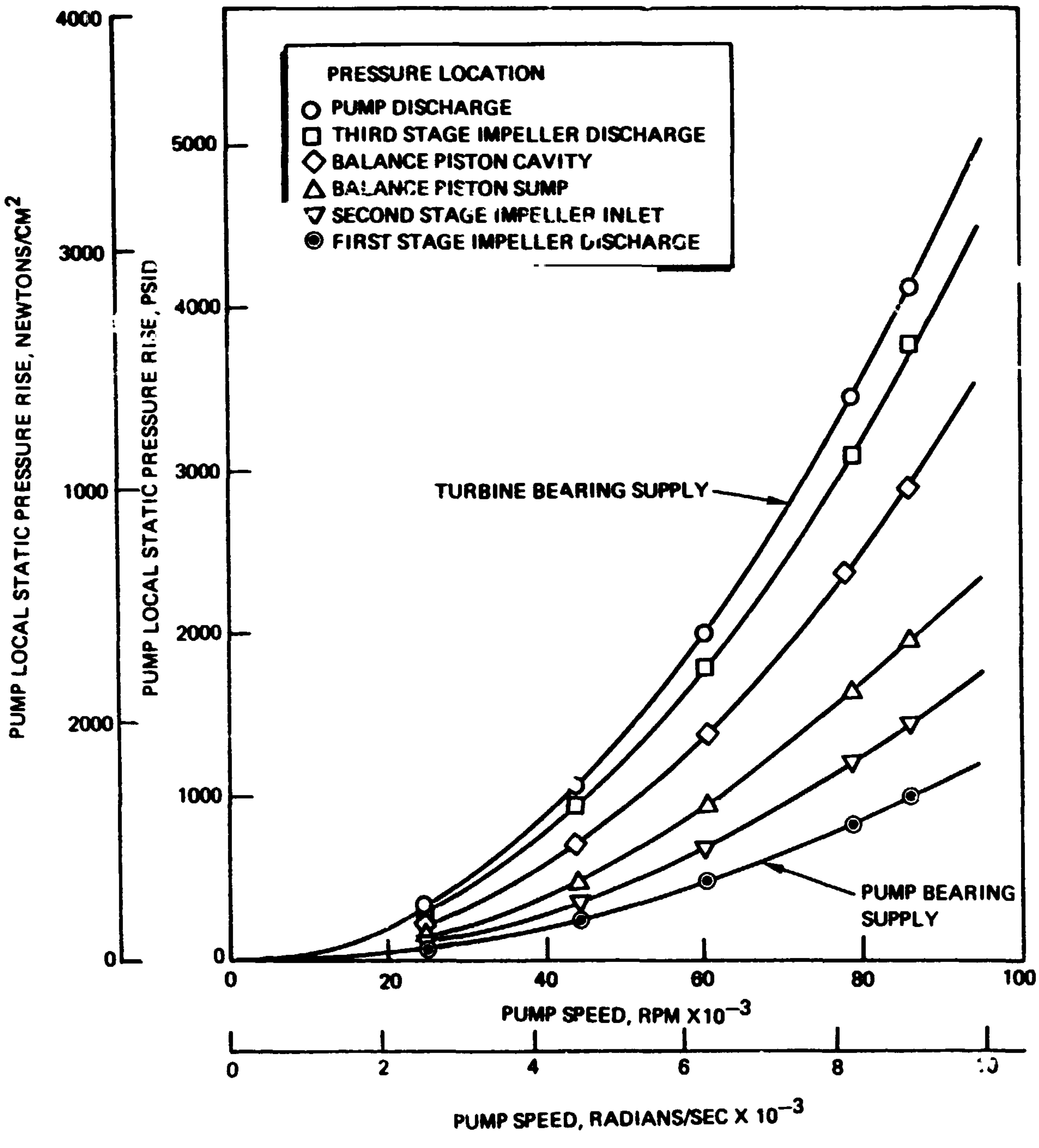

Figure 72. Typical Turbopump Internal Pressure Loads, Case C Conditions

CASE C:
SUPPLY PRESSURE VARIES AS SPEED SQUARED:

	PUMP END	TURBINE END
BASELINE: MAXIMUM SUPPLY PRESSURE AT 95,000 RPM (9948 RAD/S)	689 N/CM^2 (1000 PSI)	2482 N/CM^2 (3600 PSI)
HYDROSTATIC BEARING RADIAL CLEARANCE AT 95,000 RPM (9948 RAD/S)	0.0457 MM (0.0018 INCH)	0.0457 MM (0.0018 INCH)
ORIFICE DIAMETER	0.0762 MM (0.030 INCH)	0.0762 MM (0.030 INCH)

NO CASING OR BALL BEARING DAMPING

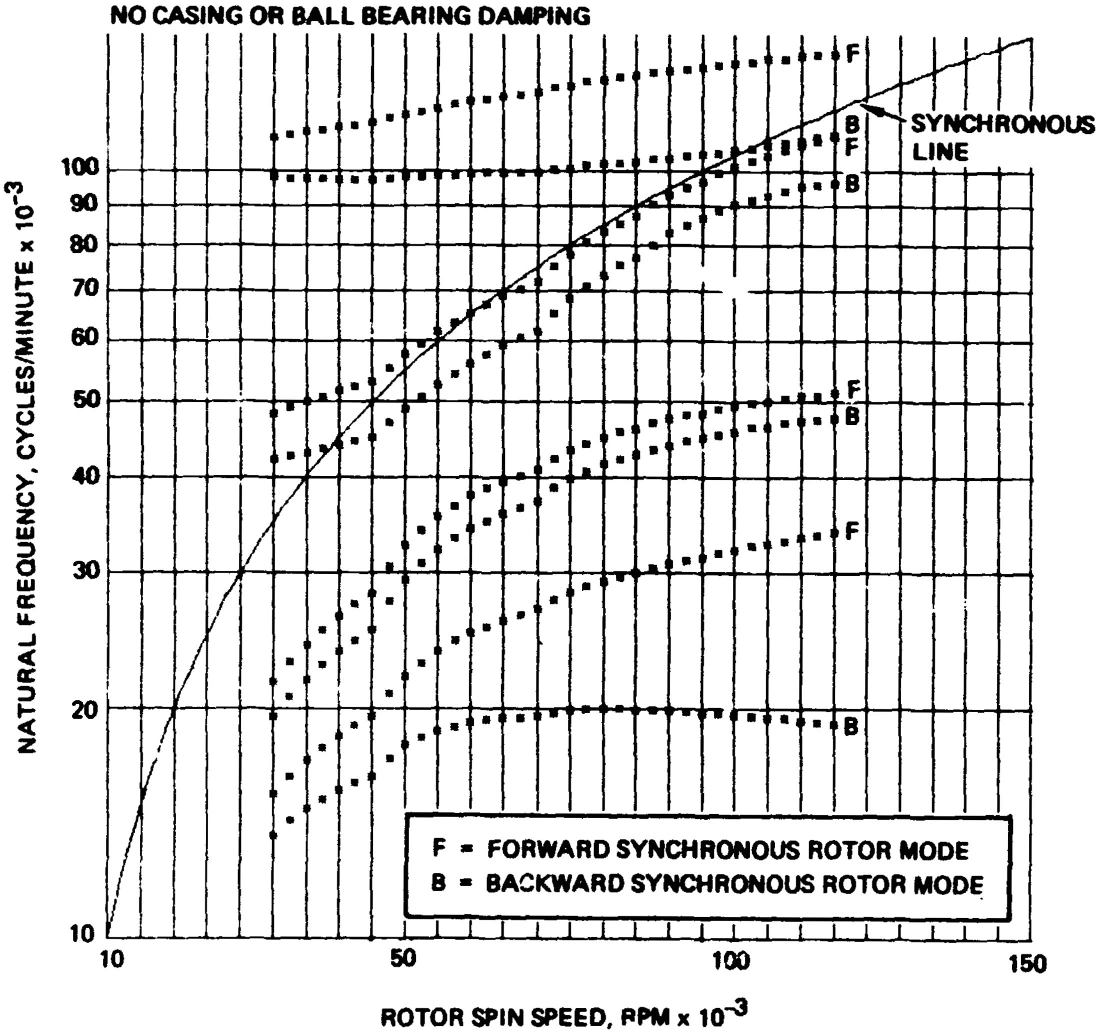

Figure 73. Turbopump Rotordynamic Characteristics - Rigid Casing, Case C Conditions

CASE C:
SUPPLY PRESSURE VARIES AS SPEED SQUARED:

	PUMP END	TURBINE END
BASELINE: MAXIMUM SUPPLY PRESSURE AT 95,000 RPM (9948 RAD/S)	689 N/CM^2 (1000 PSI)	2482 N/CM^2 (3600 PSI)
HYDROSTATIC BEARING RADIAL CLEARANCE AT 95,000 RPM (9948 RAD/S)	0.0457 MM (0.0018 INCH)	0.0457 MM (0.0018 INCH)
ORIFICE DIAMETER	0.0762 MM (0.030 INCH)	0.0762 MM (0.030 INCH)

NO CASING OR BALL BEARING DAMPING

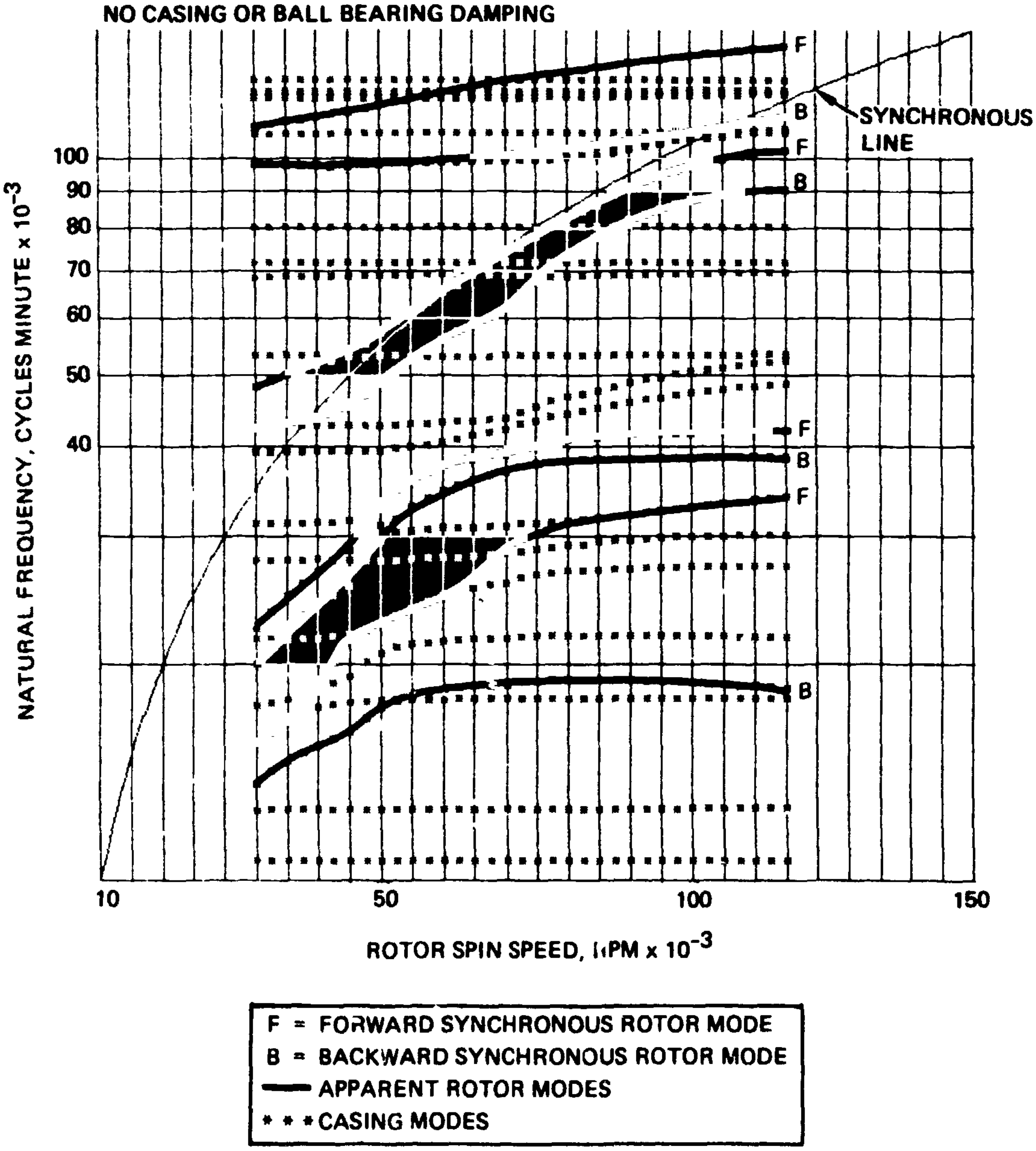

Figure 74. Turbopump Rotordynamic Characteristics - Rotor and Casing Superpositioned, Case C Conditions

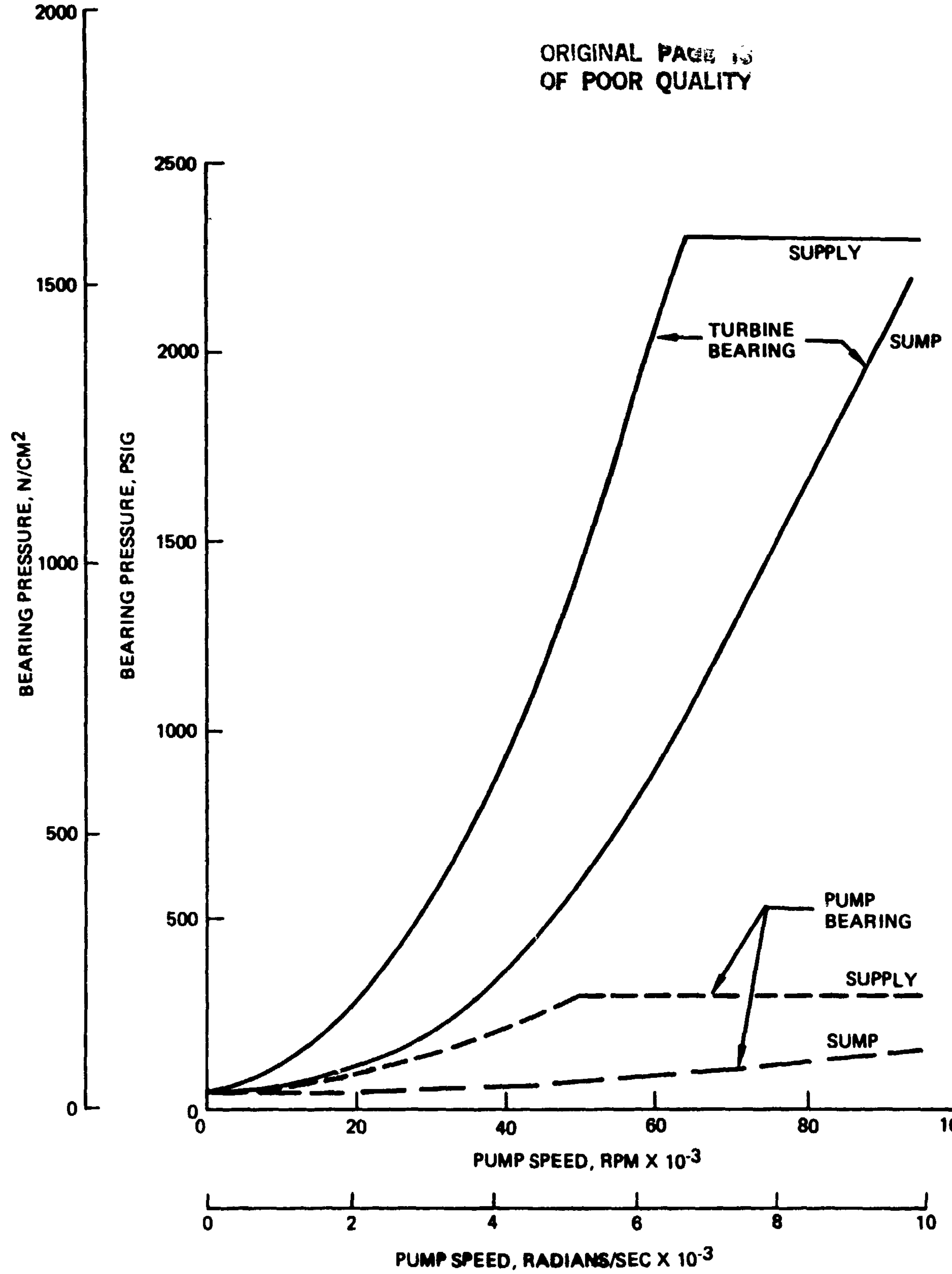

Figure 75. Hybrid Bearing Supply Pressure Profile, Case D

CASE D:

	PUMP END	TURBINE END
SUPPLY PRESSURE VARIES AS SPEED SQUARED UP TO A REFERENCE SPEED OF	5236 RAD/S (50000 RPM)	6807 RAD/S (65000 RPM)
SUPPLY PRESSURE CONSTANT ABOVE THAT SPEED	207 N/CM^2 (300 PSI)	1586 N/CM^2 (2300 PSI)
HYDROSTATIC BEARING RADIAL CLEARANCE AT 95,000 RPM	0.0457 MM (0.0018 INCH)	0.0457 MM (0.0018 INCH)
ORIFICE DIAMETER	0.762 MM (0.030 INCH)	0.762 MM (0.030 INCH)

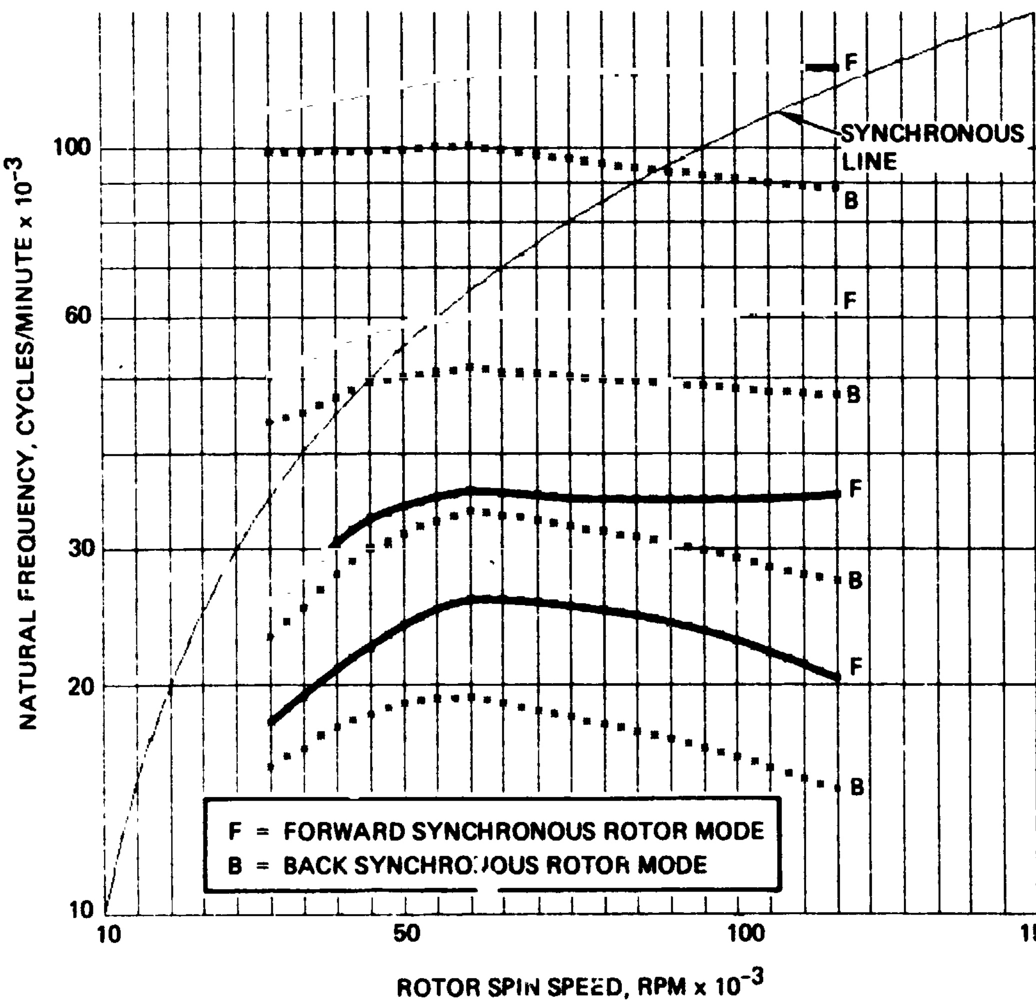

Figure 76. Turbopump Rotordynamic Characteristics -
Rigid Casing, Case C Conditions

CASE D:

	PUMP END	TURBINE END
SUPPLY PRESSURE VARIES AS SPEED SQUARED UP TO A REFERENCE SPEED OF	5236 RAD/S (50000 RPM)	6807 RAD/S (65000 RPM)
SUPPLY PRESSURE CONSTANT ABOVE THAT SPEED	207 N/CM^2 (300 PSI)	1586 N/CM^2 (2300 PSI)
HYDROSTATIC BEARING RADIAL CLEARANCE AT 95,000 RPM	0.0457 MM (0.0018 INCH)	0.0457 MM (0.0018 INCH)
ORIFICE DIAMETER	0.762 MM (0.030 INCH)	0.762 MM (0.030 INCH)

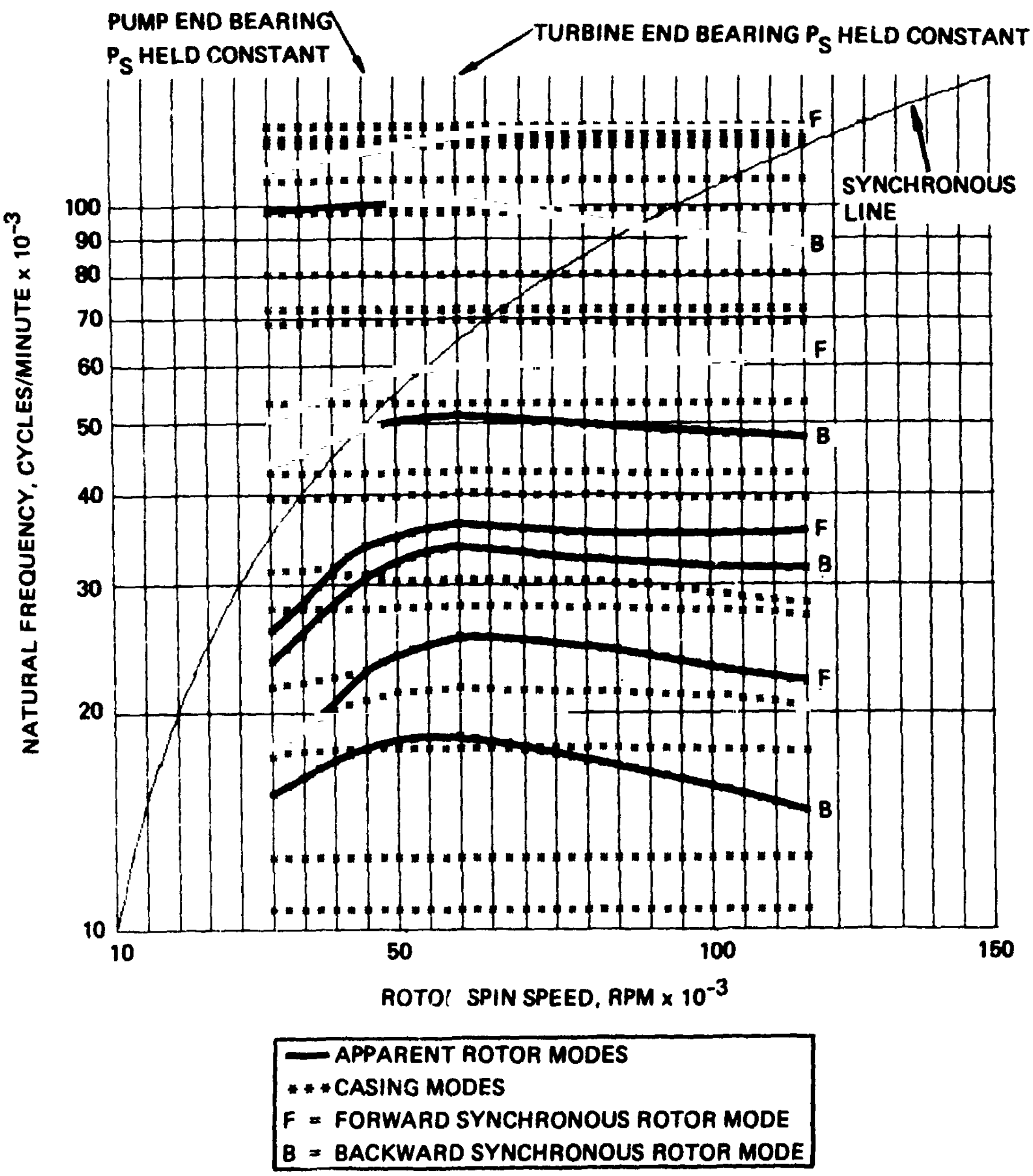

Figure 77. Turbopump Rotordynamic Characteristics - Rotor and Casing Superpositioned, Case D Conditions

with rigid casing assumptions (Fig. 76), the rotor third natural response frequency is constant at 60,000 cycles/minute above 6283 radians/sec (60,000 rpm). The superposition model using the casing and rotor combined indicates generally the same rotor modes with additional casing modes identified in Fig. 77. This case of relatively soft hydrostatic bearing stiffness satisfies the objectives of the analysis that was to verify that the third natural frequency could be held constant and moved sufficiently to allow operation above it if required. The completion of this analysis also covered the possible range of stiffness and damping available from a turbopump source of bearing supply pressure.

A summary of the two general rotor natural frequency response cahracteristics discussed as Case C and Case D is compared in Fig. 78. Each of these two approaches has possible problems when the analysis includes a stability analysis. The stability analysis was checked for the operating conditions previously defined. Case C allows supply pressure to vary as speed squared (Fig. 72) and the other (Case D) uses a constant supply pressure at high speed (Fig. 75). The stability results are shown in Fig. 79. They indicate marginal stability for the high supply pressures of Case C, if operating speeds to 9948 radians/sec (95,000 rpm) are required. During this analysis, it was generally found that for this design and a given clearance, an increase in the stiffness and damping by an increased supply pressure resulted in increased critical speed levels, as would be expected. It was also found, however, that with this increase in the supply pressure, the cross-coupling terms also change, resulting in a decrease in the stability threshold. The case for best stability (Case D) is where the very soft hydrostatic bearing supply system is used. In the analysis, the effects of casing and ball bearing damping are neglected. Operation in either of the presented modes is not completely desirable. In the Case C mode, the third critical speed follows (tracks) the synchronous speed from 6283 to 9948 radians/sec (60,000 to 95,000 rpm). In addition, the stability margin of 10,681 radians/sec (102,000 rpm) would entail a high stability risk near 9948 radians/sec (95,000 rpm) design point speeds. The use of the Case D operating characteristics indicates analytically derived stability is more than adequate, but a general concern is that of actual operation in a realm not normally encountered and generally intentionally avoided in rocket engine turbopump operation. That realm is the operation above the third critical speed and also at a speed in excess of twice the first critical speed. At 9848 radians/sec (95,000 rpm), the operating speed for this case is 4.1 times the first critical speed. The stability found by analysis using predicted damping characteristics is very good to 9848 radians/sec (95,000 rpm), but concern is that no test experience is available for this type of operation, and assessment of risk to the turbopump is difficult.

The results of this analysis were presented to the NASA-LeRC Project Manager and reviewed in detail. As a result, it was determined that for the first test series, operation of the turbopump below the third critical speed and at speeds below the final target of 9848 radians/sec (95,000 rpm) would be necessary.

Case E - Very High Supply Pressures. The possibility of running the initial test supply pressures higher than those available from the turbopump was investigated. This would, it was hoped, increase the stiffness and push the third natural frequency up above the synchronous speed line. To do this would require utilization of a high-pressure external supply of liquid hydrogen which was available for

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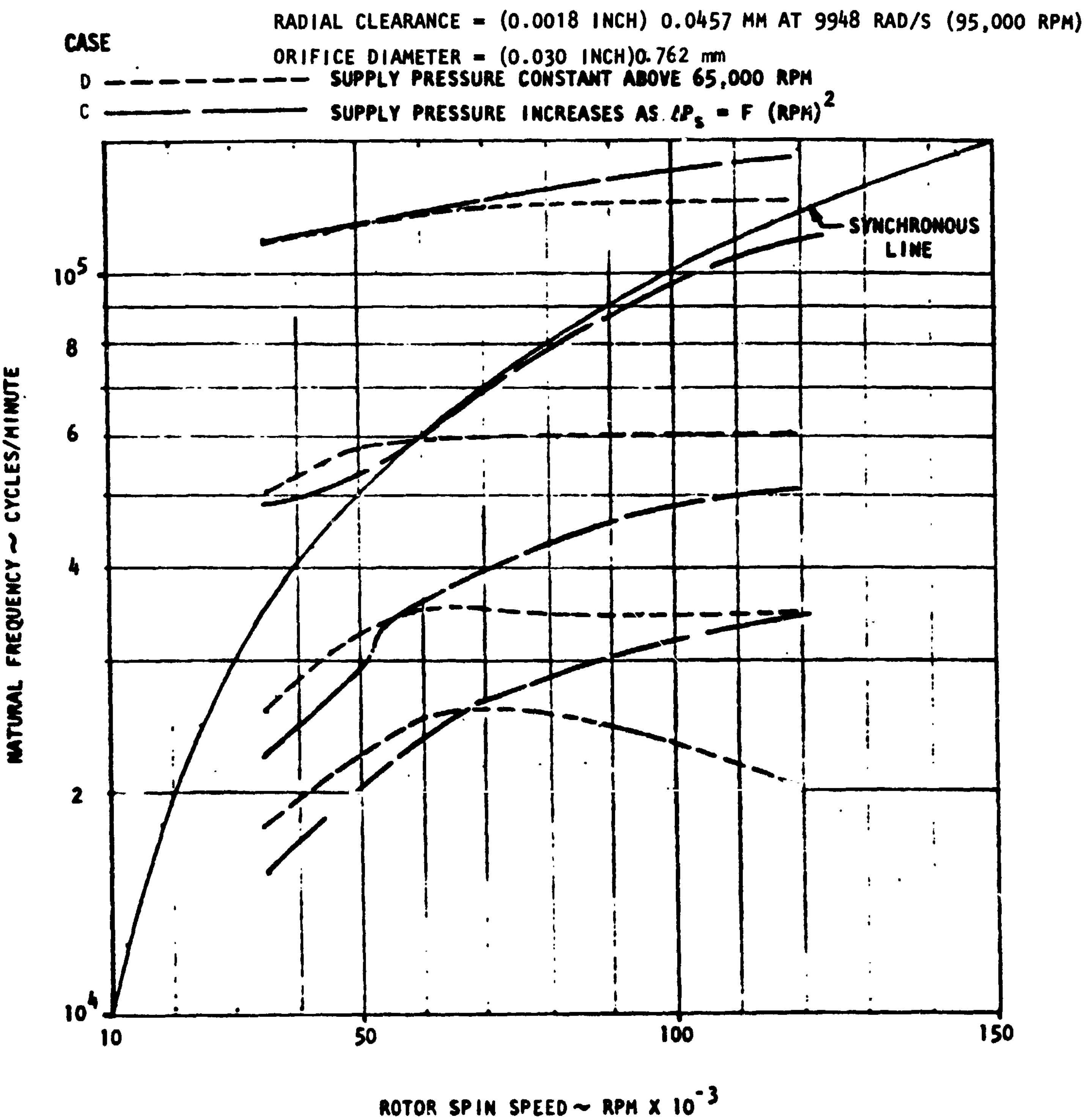


Figure 78. Rotordynamic Critical Speed Plot, Cases C and D

CLEARANCE = 0.0018 IN. (0.0457 mm)
ORIFICE DIAMETER = 0.030 IN. (9762 mm)

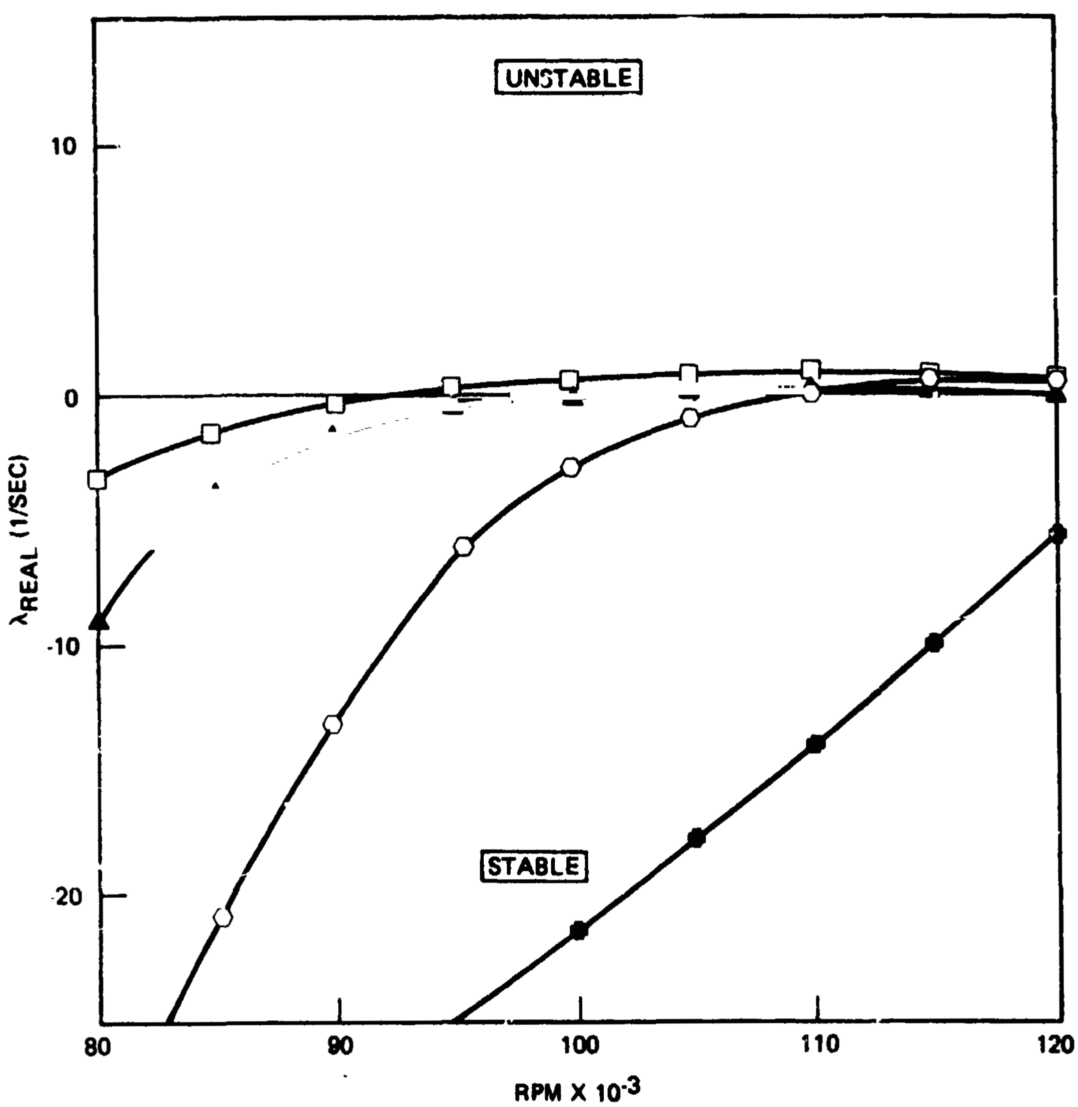
CASE

C – SUPPLY PRESSURE VARIES AS SPEED SQUARED.

□	MAXIMUM SUPPLY PRESSURE	95,000 R
▲	NOMINAL SUPPLY PRESSURE	102,000 RPM
○	MINIMUM SUPPLY PRESSURE	112,000 RPM

D – SUPPLY PRESSURE CONSTANT ABOVE 50,000 RPM PUMP, 65,000 RPM TURBINE BEARING.

● CONSTANT P_s, 300 PSI PUMP/2300 PSI TURBINE



MODEL ASSUMES:
NO CASING DAMPING
NO BALL BEARING DAMPING

Figure 79. Hybrid Bearing Stability Map, Cases C and D

these tests and could be controlled by a feedback signal from pump discharge pressure or impeller discharge pressure, as given in the facility schematic of Fig. 78.

The approach selected to accomplish this was to use a supply pressure 689 N/cm^2 (1000 psi) above the first-stage impeller discharge pressure for the pump-end bearing and 689 N/cm^2 (1000 psi) above pump discharge pressure for the turbine end to a maximum of 2758 N/cm^2 (4000 psi), Fig. 80. Using these ground rules and setting the hydrostatic bearing radial clearance at 0.0305 mm (0.0012 inch) at 9848 radians/sec (95,000 rpm), and an orifice diameter of 0.610 mm (0.024 inch), the hydrostatic bearing operating parameters were calculated and are given in Fig. 81 through 84. These results were then used in the rotordynamic analysis. The results are given in Fig. 85 and 86. The data indicate that for an assumed rigid casing (Fig. 85), the first, second, and third critical speeds are at 2618, 4712, and 12,357 radians/sec (25,000, 45,000, and 118,000 rpm) for the forward processional modes. The original ball bearing only critical speeds with rigid casing assumptions were predicted at 3141, 5550, and 14,556 radians/sec (30,000, 53,000 and 139,000 rpm), which indicates the hybrid bearing effective stiffness values are close to those of the ball bearing only case. Further analysis using the superposition techniques developed shows little difference in the predicted rotor critical speeds. This is presented in Fig. 86, which also gives the casing natural frequencies calculated for the model. The results show that speeds of 3665, 5760 to 7016, and 7854 to 9925 radians/sec (35,000, 55,000 to 67,000, and 75,000 to 90,000 rpm) are areas where turbopump operation could be held without appreciable vibration problems. The data also showed that stability would be no problem over the speed range, and instability occurs at a minimum of 10,891 radians/sec (104,000 rpm).

The leakage or flowrate through the externally pressurized bearings was calculated for the supply pressure profiles given in Fig. 80. These results are given in Fig. 87. Note the decrease in flow at the high speed comes from a decreasing clearance and on the turbine-end bearing from a decreasing pressure drop across the bearing at high speeds.

Clearance and Orifice Size Selection. The results of the analysis indicated that the broadest range of operating capability for the turbopump would be the use of the 0.0305 mm (0.0012 inch) radial clearance bearing at 9848 radians/sec (95,000 rpm) for the initial tests. For this clearance, the orifice diameter sized to give a pressure ratio of 0.5 to 0.6 across the bearing at full speed was found to be 0.610 mm (0.024 inch). These were the dimensions used for the turbopump testing.

Friction Torque Analysis. To complete the analysis of the hybrid bearing, a comparison was made of friction torque on the ball bearings with the fluid film torque on the hydrostatic bearings. The results are given in Fig. 88. To make this analysis, initial predictions were made without test data. Next, predictions were made from the actual ball bearing torque, which was measured for a duplex bearing assembly with a preload of 578 N (130 pounds). The torque changes due to the effects of chilling and increasing the inner race speed to 9848 radians/sec (95,000 rpm) with the outer race stationary were calculated and are shown in Fig. 88. Then, with the inner race at 9848 radians/sec (95,000 rpm), the effect

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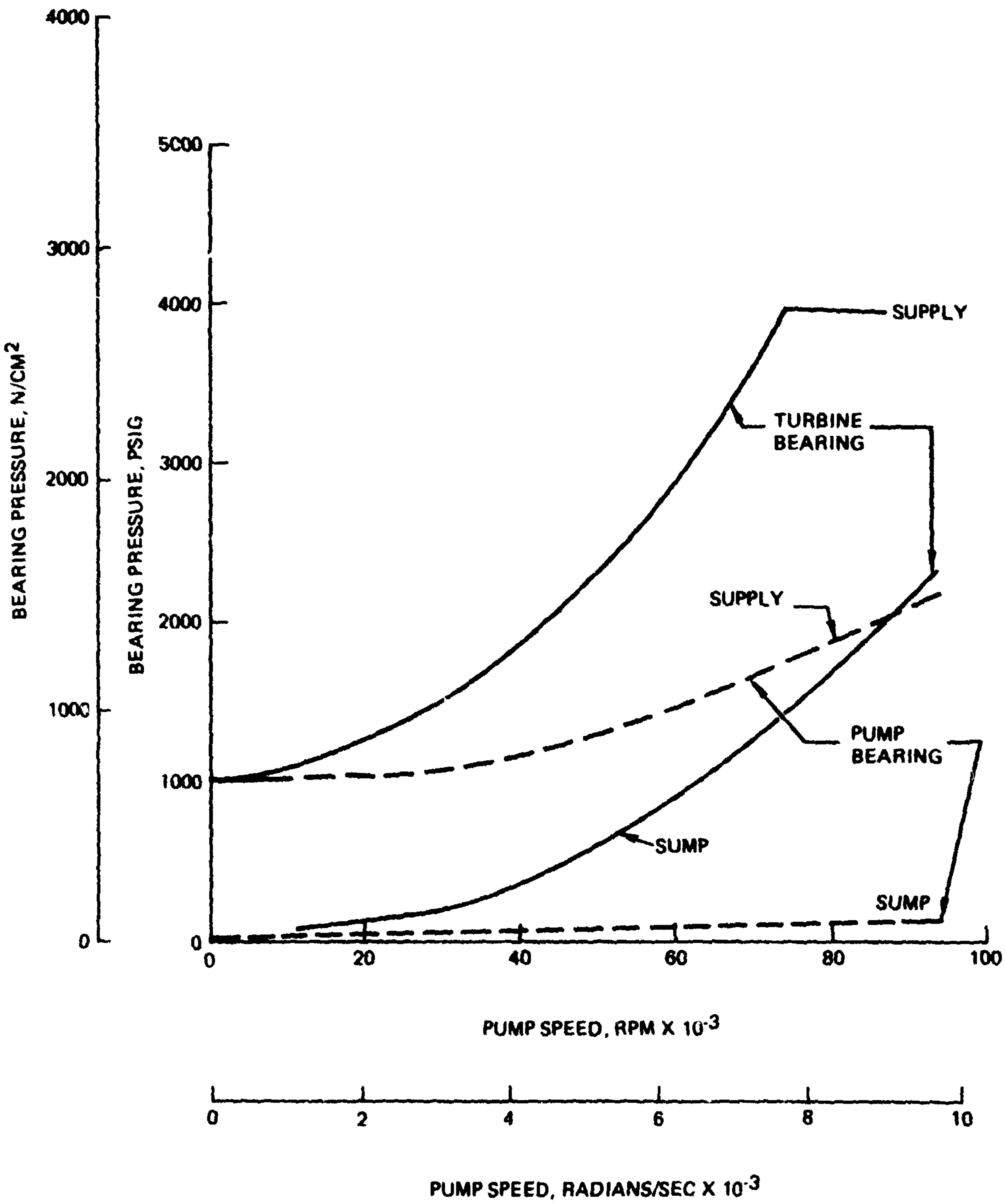

Figure 80. Hydrostatic Bearing Supply Pressure From External Source, Case E Condition

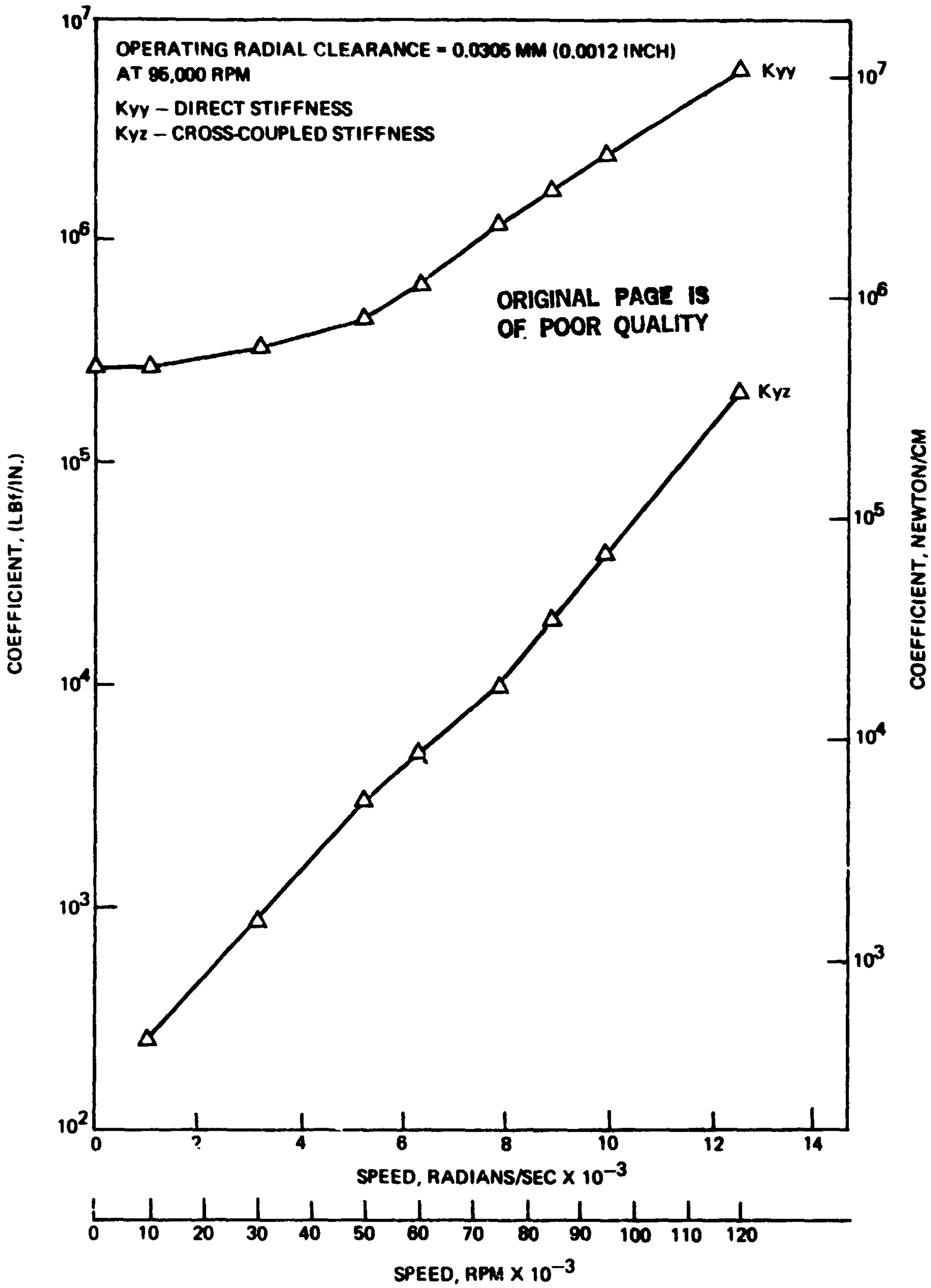

Figure 81. Pump-End Hydrostatic Bearing Direct and Cross-Coupled Stiffness, Case E Conditions

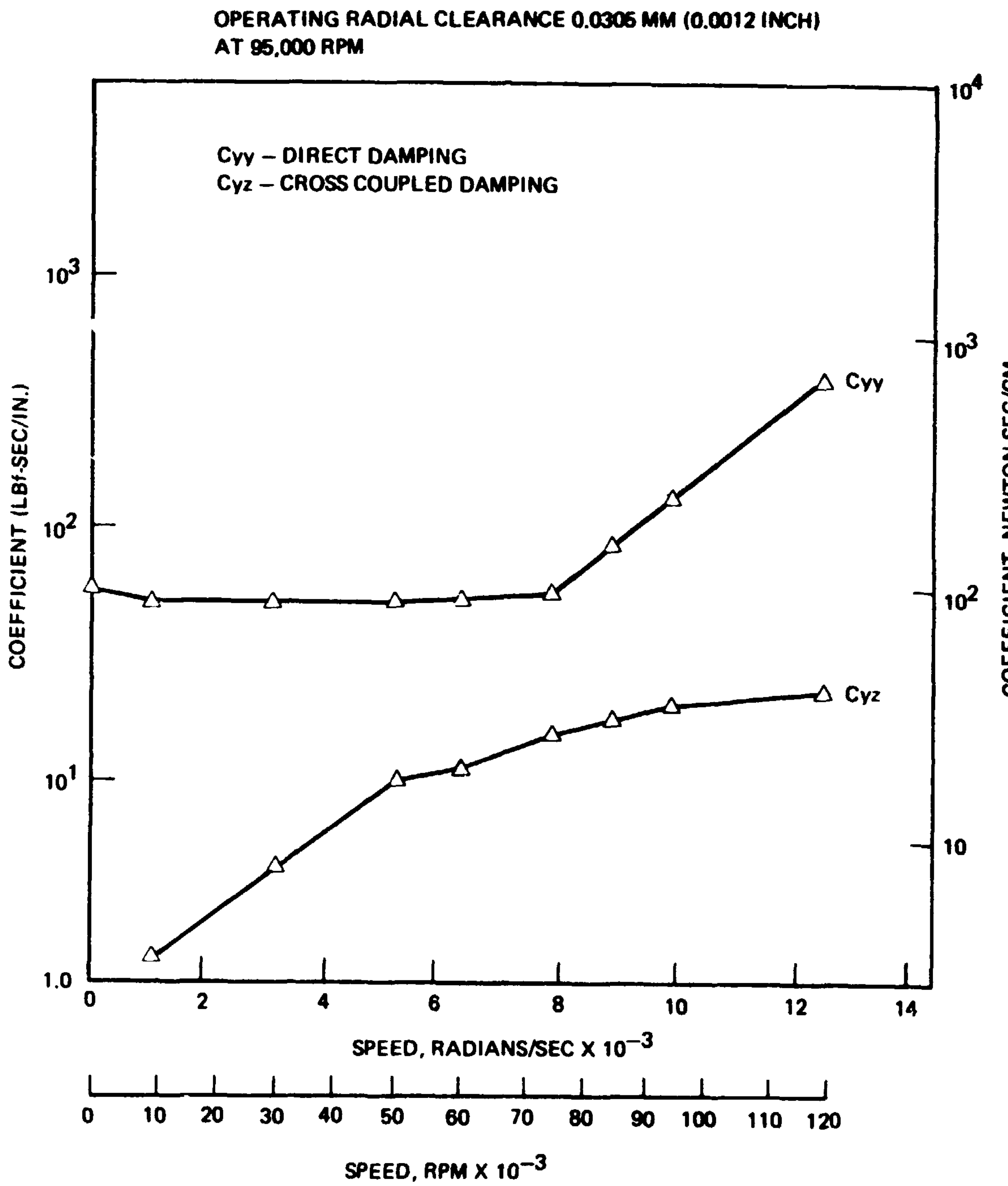

Figure 82. Pump-End Hydrostatic Bearing Direct and Cross-Coupled Damping, Case E Conditions

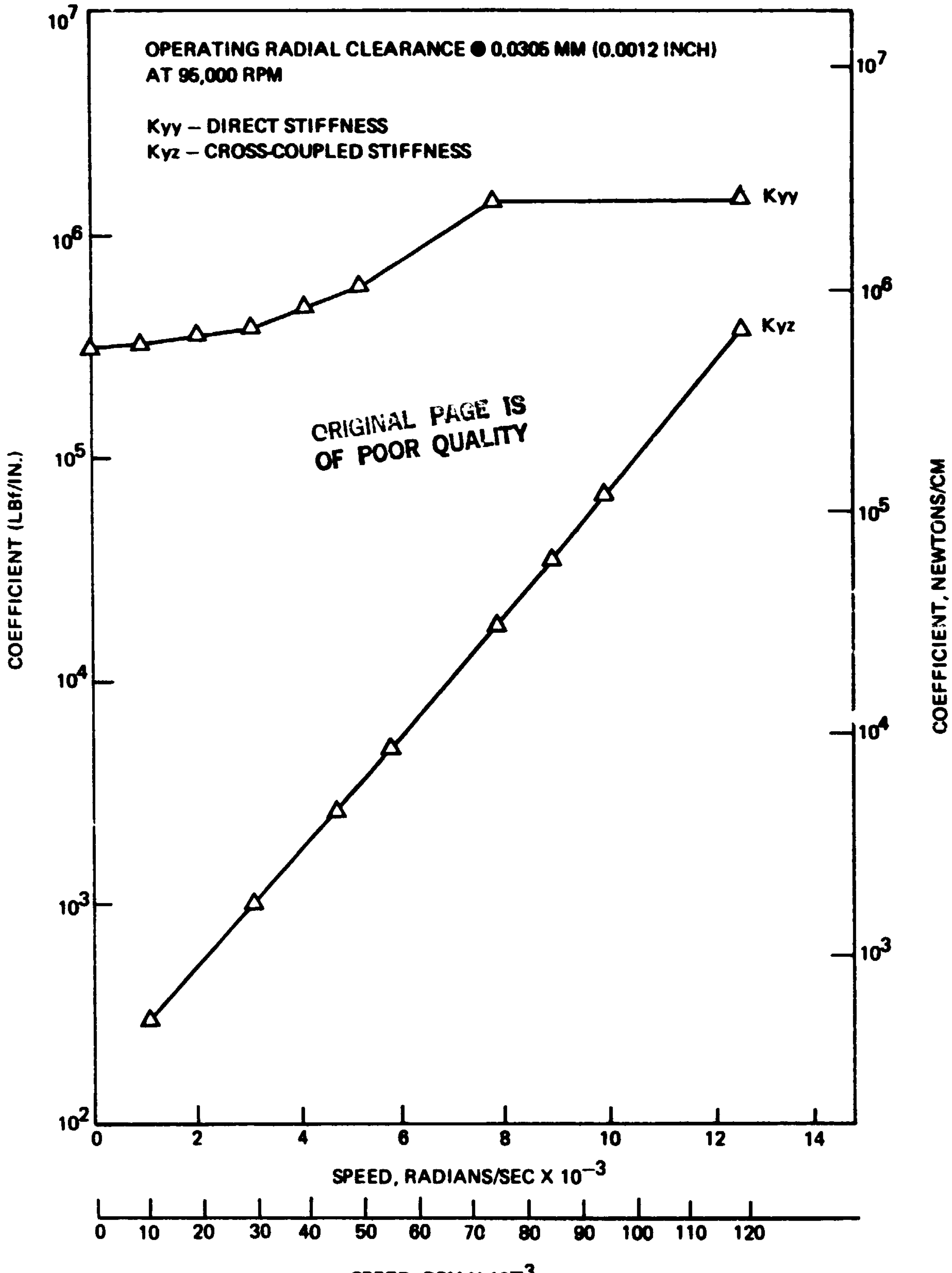

Figure 83. Turbine-End Hydrostatic Bearing Direct and Cross-Coupled Stiffness, Case E Conditions

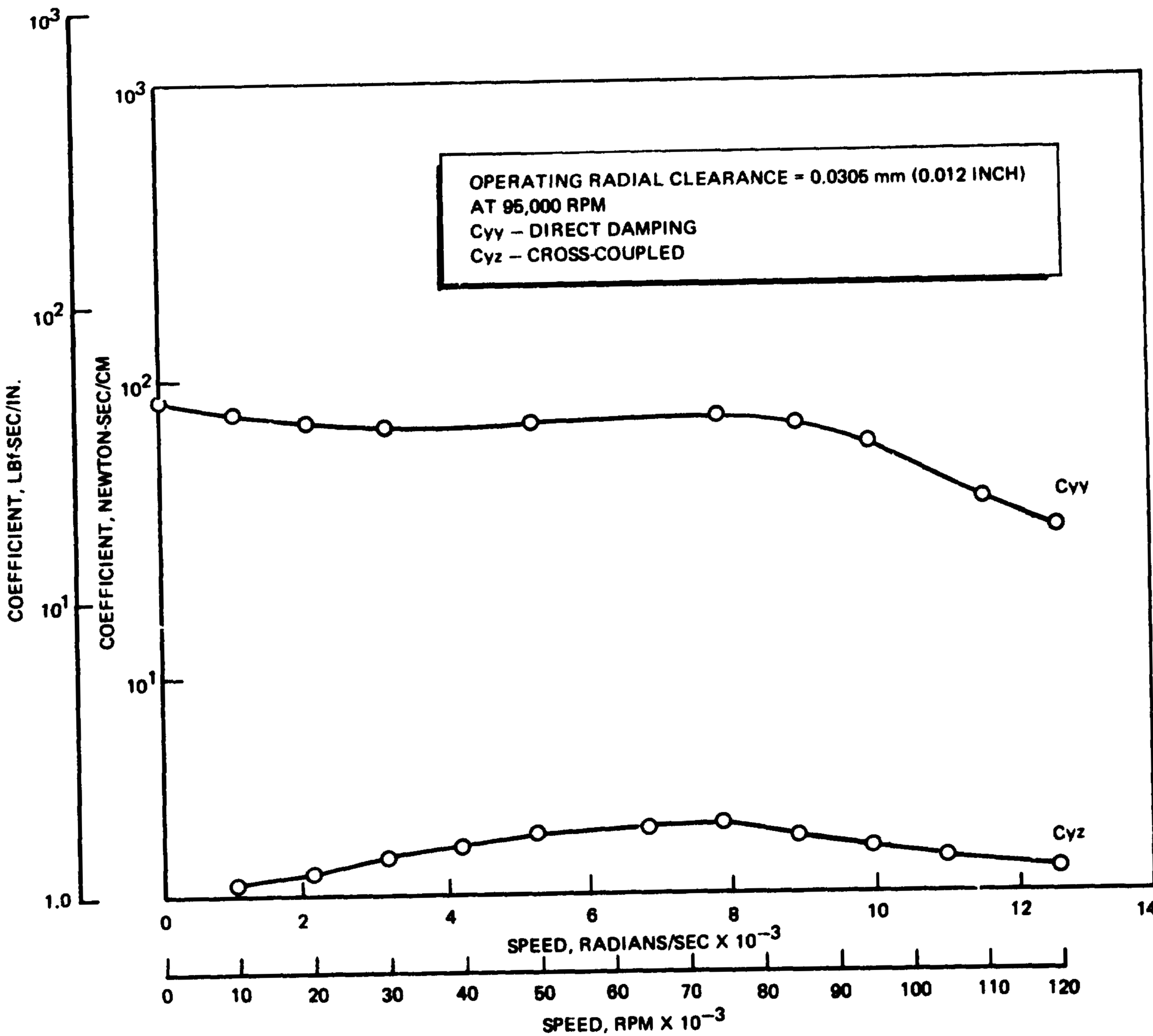

Figure 84. Turbine-End Hydrostatic Bearing Direct and Cross-Coupled Damping, Case E Conditions

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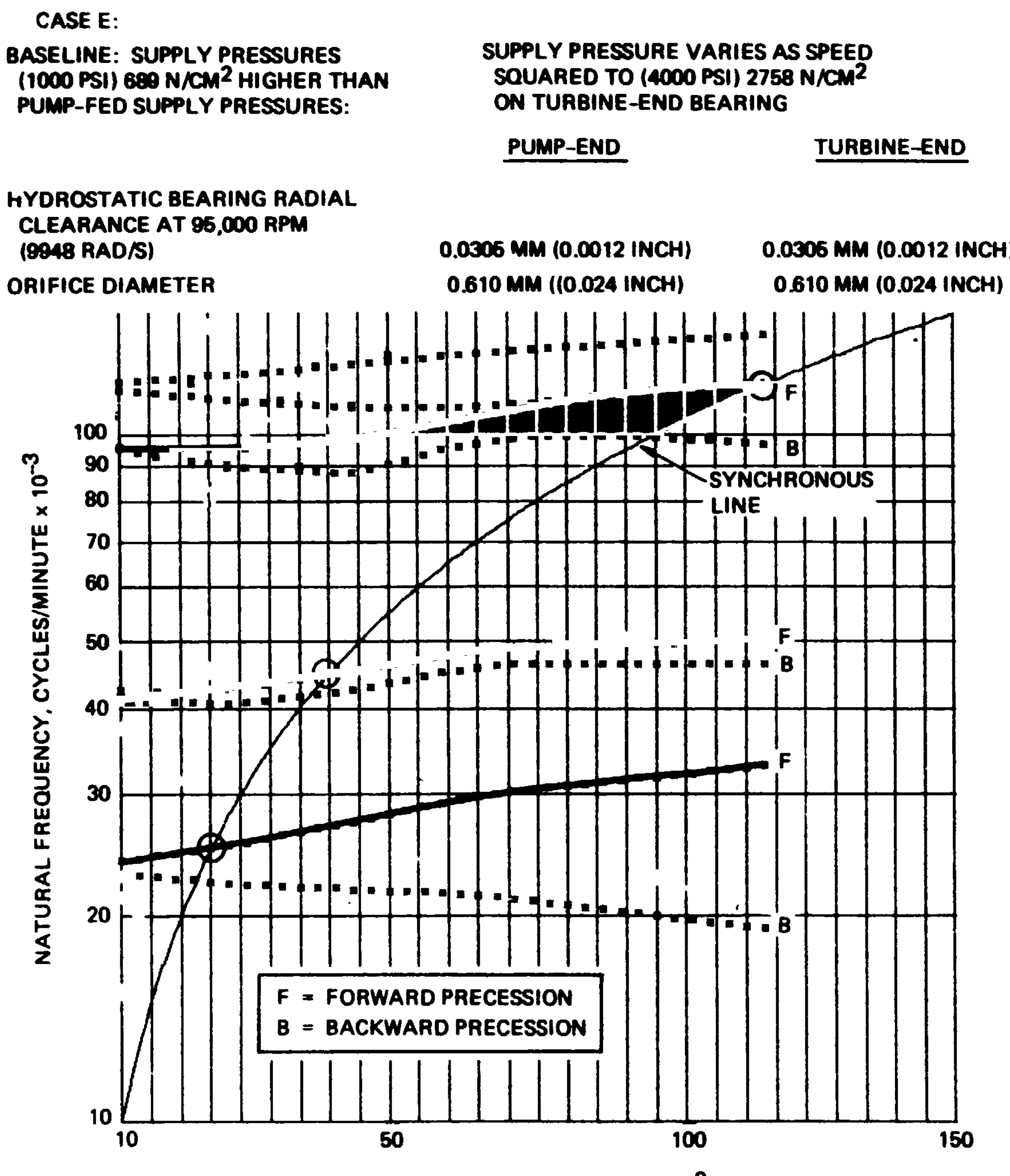

Figure 85. Turbopump Rotordynamic Characteristics - Rigid Casing, Case E Conditions

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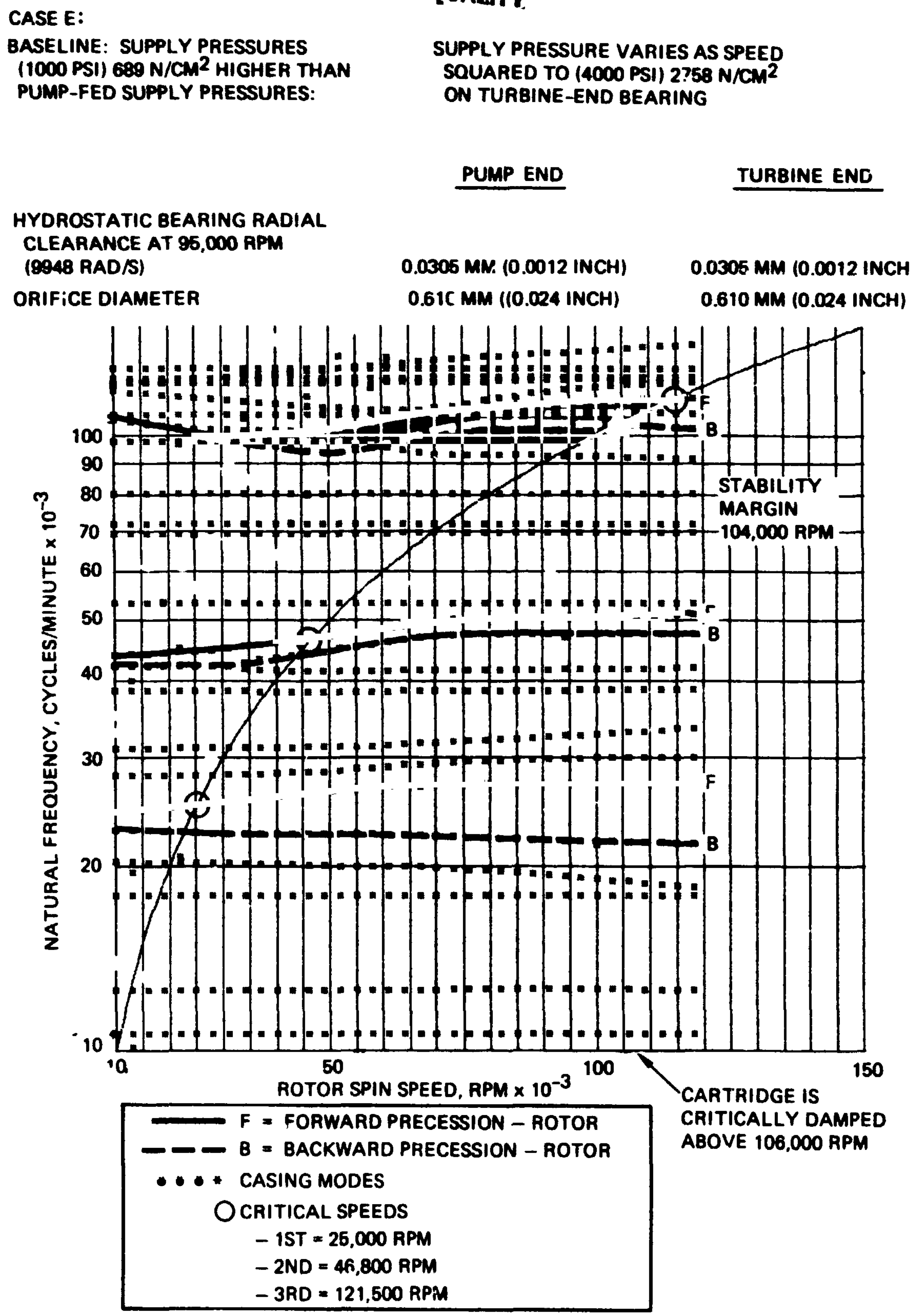

Figure 86. Turbopump Rotordynamic Characteristics - Rotor and Casing Superpositioned, Case E Conditions

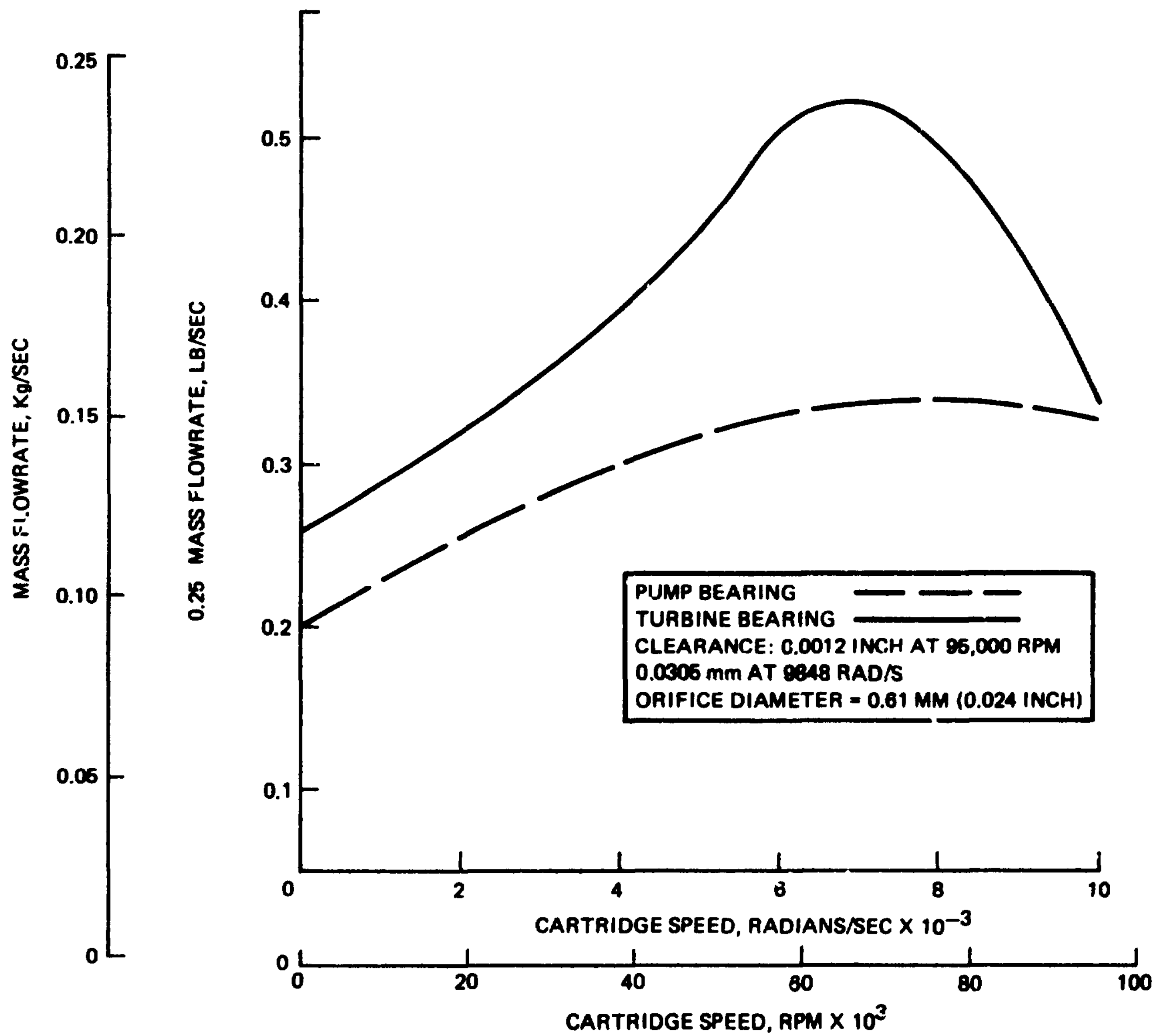

Figure 87. Hybrid Bearing Predicted Hydrostatic Supply Flow, Case E Condition

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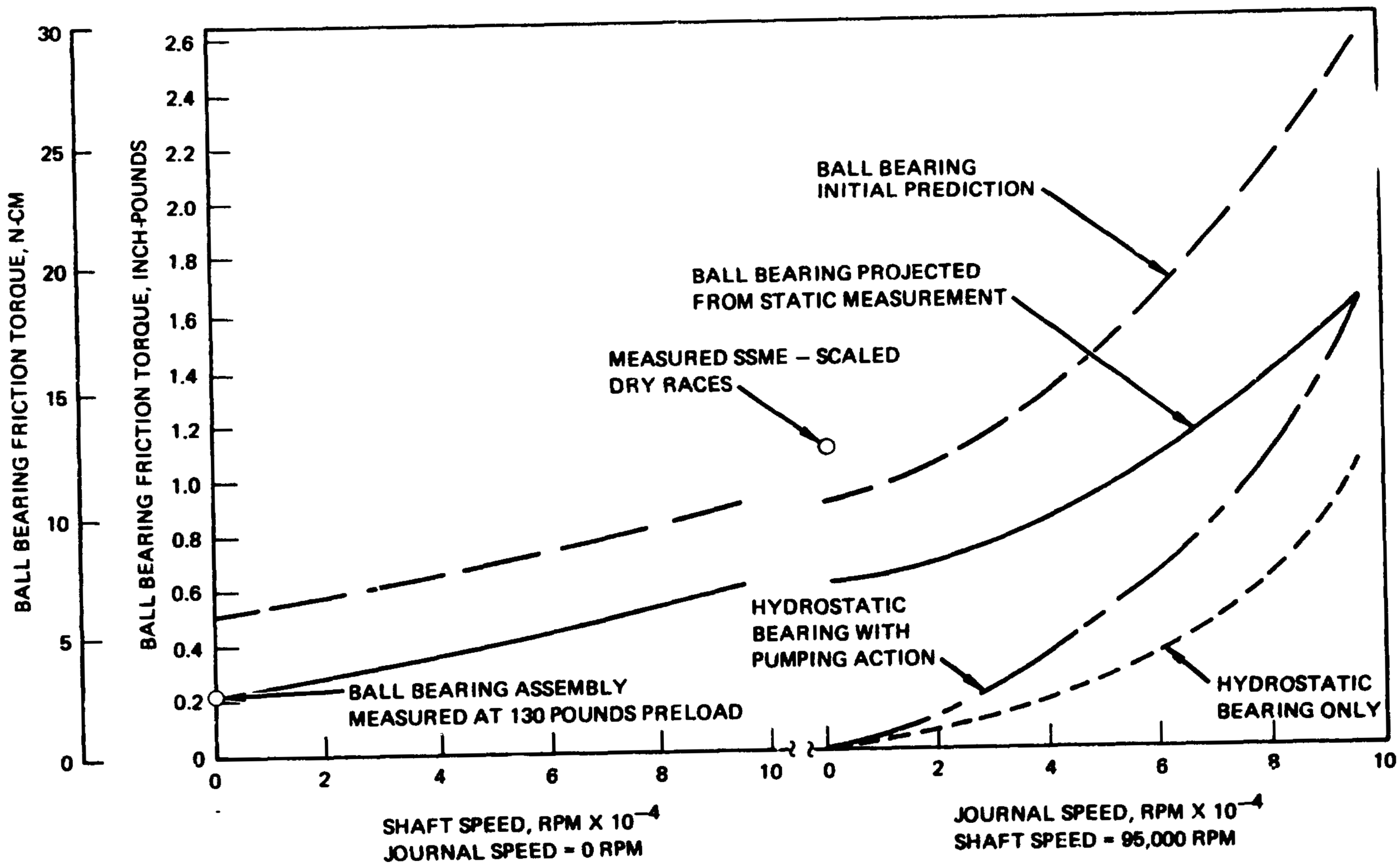

Figure 88. Ball Bearing/Hydrostatic Bearing Torque Comparisons

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of increasing the cartridge (and outer ball race) to full speed was calculated and is given in Fig. 88. Compared with this is the hydrostatic bearing fluid friction torque only which is well below ball-bearing torque. This indicates the hydrostatic cartridge will rotate with the shaft and with the ball bearings not rolling. Also shown is the effect of pumping action on the turbine end cartridge due to the hydrostatic bearing drain holes in the front side of the cartridge. This shows the torque could meet or exceed the ball torque at very high speeds on the turbine cartridge.

Hybrid Bearing Test Data and Performance

The Mark 48 turbopump hybrid bearing test data were analyzed to study the performance of the hydrostatic bearings at the pump and turbine ends. Data points at steady-state operation were selected and the bearing parameters plotted graphically. Nondimensional parameters were also calculated. The experimental test data were compared to the predicted values. Sixteen data points were selected among the 14 tests based on steady-state speeds and pressures environment. Tables 8 and 9 list the measured values corresponding to these data points. The data point identification number specifies the test number, test section, and the time slice number. As shown in Appendix B for example, data point identification No. 010 B/7 would mean Test No. 010, section B and time slice No. 7. Most of the data are for the pump end bearings since the turbine end hydrostatic bearing did not have rotation in most tests except in Tests 012 and 014.

Data Reduction. Commonly used hydrostatic bearing parameters were calculated and are listed in Tables 10 and 11. The following definitions were adopted in calculating the bearing parameters. The nomenclature is defined in the Nomenclature section of the report.

$$\text{Poiseuille Reynold's number, } R_e^* = \frac{2c^3\rho(Ps-Pa)\overline{P}_p}{\mu^2(1 - \frac{\overline{Y}}{n})L}$$

$$\text{Couette Reynold's number, } R_e = \frac{cR\omega\rho}{\mu}$$

$$\text{Bearing number, } \Lambda = \frac{\mu\omega RL}{G_p c^2(Ps-Pa)}$$

$$\text{Squeeze number, } \sigma = \frac{\mu\omega}{(Ps-Pa)}\left(\frac{R}{c}\right)^2$$

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TABLE 8. MARK-48 HYBRID BEARING

TEST DATA - PUMP BEARING
(S.I. UNITS)

POINT NUMBER	DATA POINT ID	SHAFT SPEED NS, RAD/S	CARTRIDGE SPEED NC, RAD/S	CLEARANCE C, MM	PRESSURE DIFFERENTIAL (Ps-Pa), N/CM^2	VISCOSITY $\mu, x10^{-8}$, $KG\text{-}S/CM^2$	DENSITY $\rho, x10^{-4}$, $KG\text{-}S/CM^4$	PRESSURE RATIO, $\bar{P}_R$	MASS FLOWRATE $\dot{M}$, KG/S
7	004/10	2338	2340	0.0602	229	0.249	4.69	0.1944	0.0506
8	004/20	2445	2445	0.0682	600	0.290	5.70	0.2161	0.0917
9	008A/22	3407	3407	0.0582	698	0.323	5.37	0.2747	0.0901
10	008B/4	6527	6528	0.0485	692	0.405	5.48	0.4198	0.0823
11	008B/15	5091	5094	0.0538	581	0.371	5.88	0.3056	0.0851
12	010B/1	4347	4342	0.0559	349	0.274	4.11	0.3134	0.0539
13	010B/7	4468	4468	0.0556	686	0.333	4.71	0.3298	0.0796
14	010B/14	8250	5830	0.0513	696	0.381	4.70	0.4812	0.0661
15	011A/3	4183	4184	0.0564	218	0.247	3.55	0.3028	0.0362
16	011A/23	3581	3576	0.0579	101	0.221	2.17	0.1955	0.0058
17	012A/8	4191	4094	0.0566	110	0.854	6.60	0.2496	0.0464
18	012B/2	2167	1877	0.0610	34	0.844	6.32	0.1726	0.0089
19	012B/7	2117	2044	0.0607	34	0.858	6.36	0.186	0.0087
1	014A/9	3119	3112	0.0589	63	0.942	6.65	0.2241	0.0369
2	014A/22	2898	2893	0.0594	56	0.962	6.68	0.2314	0.0330
3	014B/19	8045	5949	0.0508	440	0.752	6.64	0.467	0.0723

TABLE 8. (CONCLUDED)

(ENGLISH UNITS)

POINT NUMBER	DATA POINT ID	SHAFT SPEED NS, RPM	CARTRIDGE SPEED NC, RPM	CLEARANCE C, INCH	PRESSURE DIFFERENTIAL (Ps-Pa), PSIA	VISCOSITY $\mu, \times 10^{-9}$ LB-SEC/IN.^{2}	DENSITY, $\rho, \times 10^{-6}$ LB-SEC^2/IN.^{2}	PRESSURE RATIO, $\bar{P}_R$	MASS FLOWRATE M, LB/SEC
7	004/10	22,328	22,342	0.00237	332.9	0.354	4.30	0.1944	0.1115
8	004/20	23,351	23,350	0.00237	870.5	0.413	5.23	0.2161	0.2022
9	008A/22	32,536	32,535	0.00229	1012.9	0.460	4.93	0.2747	0.1986
10	008B/4	62,324	62,338	0.00191	1003.9	0.576	5.03	0.4198	0.1815
11	008B/16	48,620	48,646	0.00212	843.4	0.528	5.40	0.3056	0.1876
12	010B/1	41,514	41,460	0.00220	506.6	0.390	[illegible].77	0.3134	0.1184
13	010B/7	42,669	42,663	0.00219	995.7	0.474	4.32	0.3298	0.1755
14	010B/14	78,784	55,677	0.00202	1010.1	0.542	4.31	0.4812	0.1457
15	011A/3	39,943	39,953	0.00222	315.6	0.352	3.26	0.3028	0.0799
16	011A/23	34,197	34,154	0.00228	146.4	0.315	1.99	0.1955	0.0127
17	012A/8	40,022	39,104	0.00223	159.2	1.254	6.06	0.2496	0.1023
18	012B/2	20,695	17,927	0.00240	48.9	1.200	5.80	0.1726	0.0196
19	012B/7	20,214	19,516	0.00239	49.6	1.220	5.84	0.1860	0.0192
1	014A/9	29,783	29,724	0.00232	91.5	1.340	6.10	0.2241	0.0813
2	014A/22	27,670	27,624	0.00234	81.3	1.368	6.13	0.2314	0.0728
3	014B/19	76,827	56,804	0.00200	638.6	1.070	6.09	0.4670	0.1594

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TABLE 9. MARK 48-F HYBRID BEARING

TEST DATA - TURBINE BEARING
(S.I. UNITS)

POINT NUMBER	DATA POINT ID	SHAFT SPEED N_S, RAD/S	CARTRIDGE SPEED N_C, RAD/S	CLEARANCE C, MM	PRESSURE DIFFERENTIAL (Ps-Pa), N/CM2	MASS FLOWRATE $\dot{M}$, KG-S	VIBRATION P-P, MM	SQUEEZE NO. (σ)	VISCOSITY μ, x10-8 KG-S/CM2
20	012A/8	4191	540	0.0622	202	0.1126	0.0914	0.00241	0.926
21	012B/2	2167	1192	0.0617	49	0.0770	0.0356	0.00502	0.898
22	012B/7	2117	1012	0.0620	53	0.0774	0.0356	0.00455	0.908
4	014A/9	3119	948	0.0620	107	0.0740	0.0635	0.00350	0.962
5	014A/22	2898	890	0.0620	92	0.0689	0.0584	0.00390	0.977
6	014B/19	8045	0	0.0625	772	0.1802	0.2286	0.00116	0.895

(ENGLISH UNITS)

POINT NUMBER	DATA POINT ID	SHAFT SPEED N_S, RPM	CARTRIDGE SPEED N_C, RPM	CLEARANCE C, INCH	PRESSURE DIFFERENTIAL (Ps-Pa), PSIA	MASS FLOWRATE $\dot{M}$, LB/SEC	VIBRATION P-P, INCH	SQUEEZE NO. (σ)	VISCOSITY μ, x10-9 LB-SEC/IN.2
20	012A/8	40,022	5155	0.00245	292.6	0.2482	0.0036	0.00241	1.317
21	012B/2	20,695	11,384	0.00243	71.5	0.1690	0.0014	0.00502	1.277
22	012B/7	20,214	9669	0.00244	77.3	0.1707	0.0014	0.00455	1.292
4	014A/9	29,783	9051	0.00244	154.8	0.1631	0.0025	0.00350	1.368
5	014A/22	27,670	8495	0.00244	133.3	0.1520	0.0023	0.00390	1.389
6	14B/19	76,827	0	0.00246	1119.5	0.3972	0.0090	0.00116	1.273

TABLE 10. MARK 48-F HYBRID BEARING

REDUCED DATA-PUMP BEARING

POINT NUMBER	DATA POINT ID	R_E^*, x10^6	R_E	G_P	Λ	$\frac{N_C}{N_S}$	σ	$\bar{\dot{M}}$	VIB. AMPL., P-P INCH	VIB. AMPL., P-P MM	$\frac{PS-PA}{PA}$
7	004/10	71.0	58,935	0.024	0.0150	1.0	0.034	0.547	0.00099	0.0251	3.14
8	004/20	184.0	64,213	0.015	0.0110	1.0	0.016	0.523	0.00095	0.0241	7.92
9	008A/22	187.0	73,166	0.015	0.0160	1.0	0.023	0.455	0.00110	0.0279	8.9
10	008B/4	107.0	95,273	0.020	0.0420	1.0	0.079	0.436	0.00490	0.1245	9.53
11	008B/16	114.3	96,645	0.020	0.0287	1.0	0.054	0.460	0.00240	0.0610	7.84
12	010B/1	100.7	80,791	0.020	0.0280	1.0	0.053	0.450	0.00175	0.4450	4.67
13	010B/7	159.0	78,026	0.015	0.0240	1.0	0.034	0.460	0.00175	0.4450	8.82
14	010B/14	141.0	81,950	0.015	0.0414	0.71	0.083	0.375	0.00720	0.1829	9.63
15	011A/3	66.1	75,269	0.025	0.0307	1.0	0.072	0.410	0.00260	0.0660	2.97
16	011A/23	16.3	45,077	0.045	0.0266	1.0	0.113	0.160	0.00270	0.0686	1.38
17	012A/8	4.08	38,613	0.080	0.0656	0.977	0.510	0.740	0.00360	0.0914	1.55
18	012B/2	1.13	19,055	0.140	0.0462	0.866	0.710	0.310	0.00140	0.0356	0.46
19	012B/7	1.19	20,459	0.140	0.0510	0.965	0.700	0.280	0.00140	0.0356	0.461
1	014A/9	2.10	28,765	0.110	0.0620	0.998	0.650	0.781	0.00250	0.0635	0.886
2	014A/22	1.90	26,533	0.110	0.0654	0.998	0.680	0.754	0.00230	0.0584	0.774
3	014B/19	30.50	59,249	0.035	0.0580	0.74	0.260	0.413	0.00900	0.2286	6.46

TABLE 11. MARK 48-F HYBRID BEARING

REDUCED DATA - PUMP BEARING

POINT NUMBER	DATA POINT ID	FILM RESISTANCE, R_F ($SEC^2/LB\text{-}IN.^2$)	R_F ($SEC^2/N\text{-}CM^2$)	ORIFICE RESISTANCE R_O ($SEC^2/LB\text{-}IN.^2$)	R_O ($SEC^2/N\text{-}CM^2$)	$\bar{R}_r$	$\bar{R}_O$	C/R
7	004/10	5205	181	21,572	752	[illegible]	2.7	0.00271
8	004/20	4601	160	16,690	582	0.789	2.86	0.00271
9	008A/22	7055	246	18,626	649	1.33	3.5	0.00262
10	008B/4	12,793	446	17,681	616	2.21	3.06	0.00220
11	008B/16	7324	255	16,641	580	1.446	3.28	0.00242
12	010B/1	11,326	395	24,812	[illegible]	1.58	3.45	0.00251
13	010B/7	10,662	372	21,666	755	1.57	3.19	0.00250
14	010B/14	22,897	798	24,686	[illegible]	3.42	3.68	0.00231
15	011A/3	14,969	522	34,467	[illegible]	1.83	4.22	0.00254
16	011A/23	177,452	6184	730,230	25,446	7.44	3.06	0.00261
17	0.12A/8	[illegible]	132	11,415	398	0.457	1.37	0.00255
18	012B/2	21,970	766	105,320	3670	1.85	8.86	0.00275
19	012B/7	25,026	872	109,523	3816	2.37	1.04	0.00273
1	014A/9	3102	109	10,741	374	0.368	1.27	0.00265
2	014A/22	3550	124	11,790	411	0.406	1.35	0.00267
3	014B/19	[illegible]	409	13,396	467	2.74	3.13	0.00229

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$$\text{Dimensionless flowrate, } \bar{\dot{m}} = \frac{\mu(\frac{L}{D})(1 - \frac{\bar{y}}{n})\dot{m}}{G_p c^3 \bar{P}_R (Ps-Pa)g}$$

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$$\text{Film resistance, } R_f = \frac{Pr-Pa}{(\dot{m})^2}$$

$$\text{Orifice resistance, } R_o = \frac{Ps-Pr}{(\dot{m})^2}$$

$$\text{Dimensionless film resistance, } \bar{R}_f = \left[\frac{\rho g G_p c^3 \bar{P}_R}{\mu(\frac{L}{D})(1 - \frac{\bar{y}}{n})}\right]^2 (Ps-Pa)R_f$$

$$\text{Dimensionless orifice resistance, } \bar{R}_o = \left[\frac{\rho g G_p c^3 \bar{P}_R}{\mu(\frac{L}{D})(1 - \frac{\bar{y}}{n})}\right]^2 (Ps-Pa)R_o$$

The viscosity correction factor for turbulence, G_p, is obtained from Fig. 89, assuming hydrostatic dominance (Ref. 4). The geometric dimensions of the bearings are:

Bearing length, L = 0.925 inch = 2.35 cm

Journal radius, R = 0.875 inch = 2.22 cm

Number of rows, n = 2

Recess width, Lp = 0.095 inch = 2.41 mm

Recess parameter, $\bar{y} = 0.2 = \frac{nL_p}{L}$

This assumes the recesses are staggered without overlapping and the axial pressure gradient dominates the flow.

Each bearing parameter will be discussed in detail in the subsequent paragraphs.

Mass Flowrate. The measured flowrate was plotted against the pressure differential across the bearing in Fig. 90. The data from Tables 8, 10, and 11 are given numbers for each data point to aid in cross correlation as required. A gradual increase in flowrate with increasing Δp was observed in the data. The test data were compared to the predicted values for several points, as shown in Fig. 90. The results indicate that actual flow values are much lower than predicted.

A direct comparison of predicted flowrate, versus actual measured flowrate is difficult due to the differences in predicted pressures to operating supply pressures at the various speeds tested. A general comparison can be made for the pump-end bearing using data from test 008 and comparing it to the predictions of flow given in Fig. 87 for high external supply pressure levels achieved near the analytical

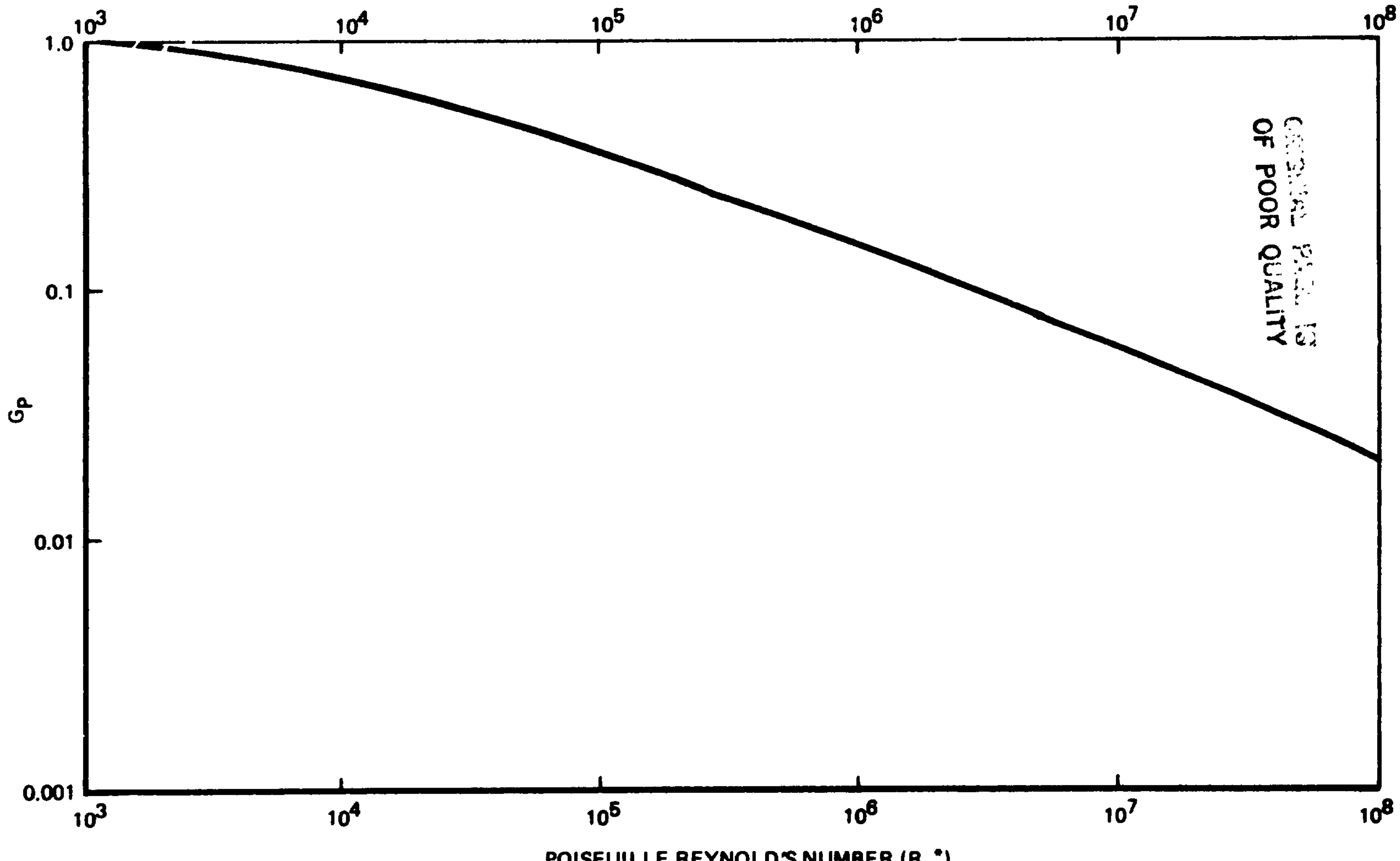

Figure 89. Turbulent Correction Factor for Viscosity, μEffective = μ/Gp

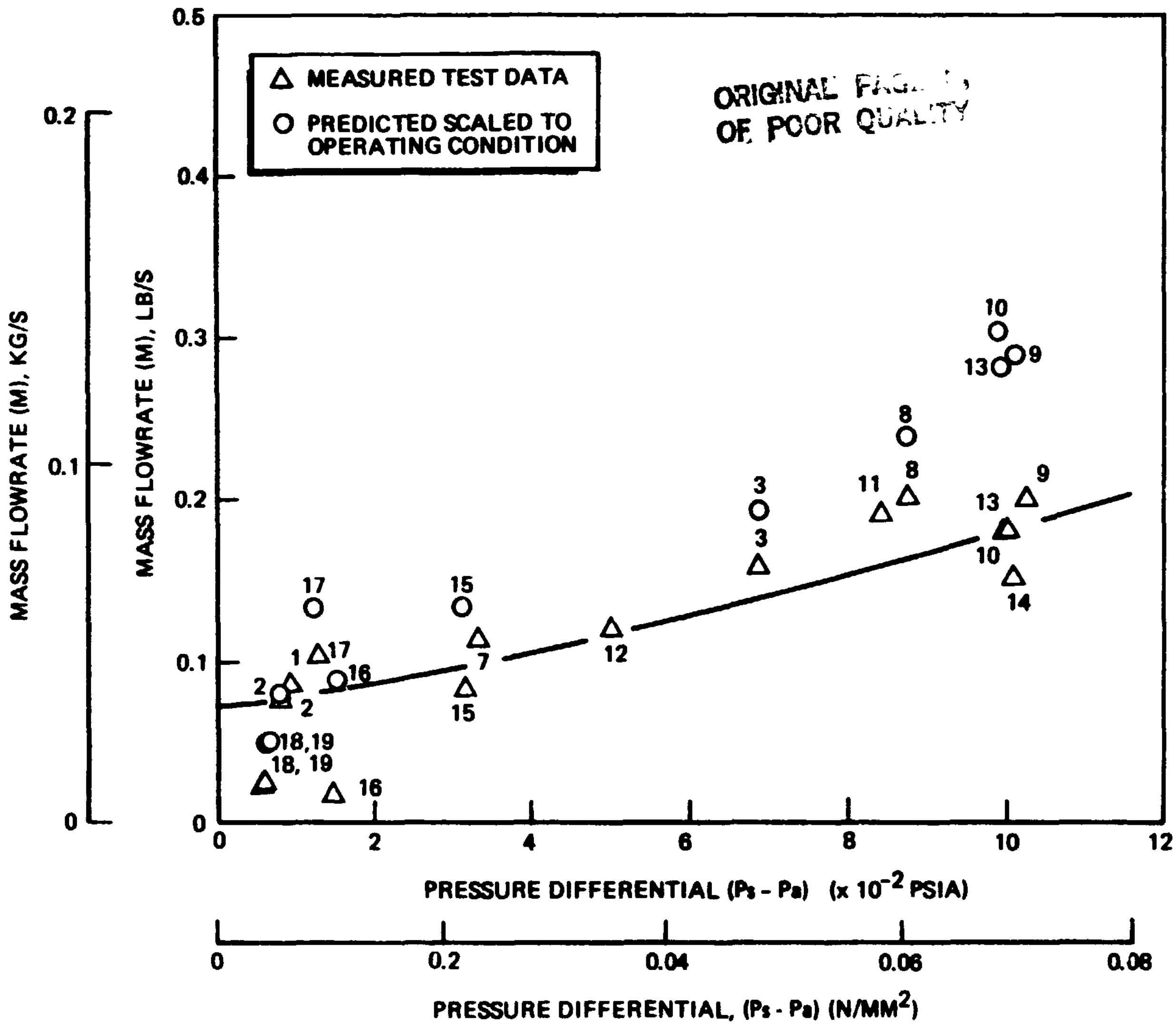

Figure 90. Hybrid Bearing Mass Flowrate vs Pressure Differential

targets shown in Fig. 80 (as case E). This occurs at test point (5) as previously described in Fig. 47 around the speed of 3403 radians/sec (32,500 rpm). The data in Appendix B gives for Test 008A - Slices 19-23 the supply pressures of 762 N/cm^2 (1106 psia) at a speed of 3403 radians/sec (32,500 rpm). The flow rates measured are approximately 0.095 kg/s (0.210 lb/sec, while the predicted flowrates from Fig. 87 are 0.130 kg/s (0.285 lb/sec). This is to say that the measured flow is approximately 30% lower than predicted for external supply flow. This may be due in part to the high temperature of the external flow which causes some choking effects at the fluid film discharge. This variation from the prediction can also be accounted for in terms of frictional effects and will be discussed in detail in a later section of this report in discussion of improved modeling techniques.

The dimensionless flowrate exhibits generally constant values within the large data scatter with increasing pressure ratio (Ps-Pa)/Pa (Fig. 91). The data falls into two categories generally: that of external supply fluid (warmer) and that of internal supply (cooler) fluid. The pressure ratio used in this graph is the total pressure differential across the bearing including the pressure drop across the orifice. If the data are plotted with the dimensionless flowrate against $\overline{P}_R$ = (Pr-Pa)/Pa, Fig. 92, the same constant trend is also observed.

The effect of clearance on the dimensionless flowrate can be seen in Fig. 93, the data are too scattered to show a trend of $\bar{\dot{m}}$ with increasing (c/R). The data are grouped somewhat as a function of (Ps-Pa)/Pa. Theory predicts that $\bar{\dot{m}}$ increases with c/R.

The effect of rotational speed on flowrate is illustrated in Fig. 94. A general slight decrease in flowrate with increased bearing number Λ is observed. The bearing number Λ value is greater at higher cartridge speed, which also reduces the clearance. The influence of Λ on flowrate is, therefore, a combined effect from the cartridge speed and the clearance. Expressing the flowrate in dimensionless form ($\bar{\dot{m}}$) should remove the clearance effect (Fig. 95). It can be seen, however, that $\bar{\dot{m}}$ is decreasing generally with Λ. This indicates that, for general turbopump application using hybrid bearings, the rotational and other effects on flowrate other than the clearance effect may not be negligible. Choking effects may also be indicated here. Due to higher film resistance, the pressure rate $\overline{P}_R$ increases with the cartridge speed (Fig. 96 and 97) and may affect the flowrate slightly. With regard to choking, a general review of the data indicates that data points 16, 18, and 19 are likely choked, as their predictions for flowrate are in disagreement with measured data by amounts much greater than the other data.

Cartridge Speed Ratio (Nc/Ns). The pump end hydrostatic cartridge tracked the shaft speed very closely until the latter reached approximately 7330 radians/sec (70,000 rpm) beyond which the speed ratio starts to decline (Fig. 98).

A speed lag in the pump cartridge occurred during Test 010 when the shaft was accelerated from 4189 to 8378 radians/sec (40,000 to 80,000 rpm), Fig. 99. The sharp spikes of the speed signal suggested some contact rubbing did happen. A data point (010B/14) was selected to analyze this speed phenomenon. The calculated stiffness at this data point was estimated to be 700,472 N/cm (400,000 lbf/in.) and its radial clearance of 0.0513 mm (0.00202 inch). The radial load required to cause contact will be 700,472 N/cm x 0.00513 cm ≅ 3558 N

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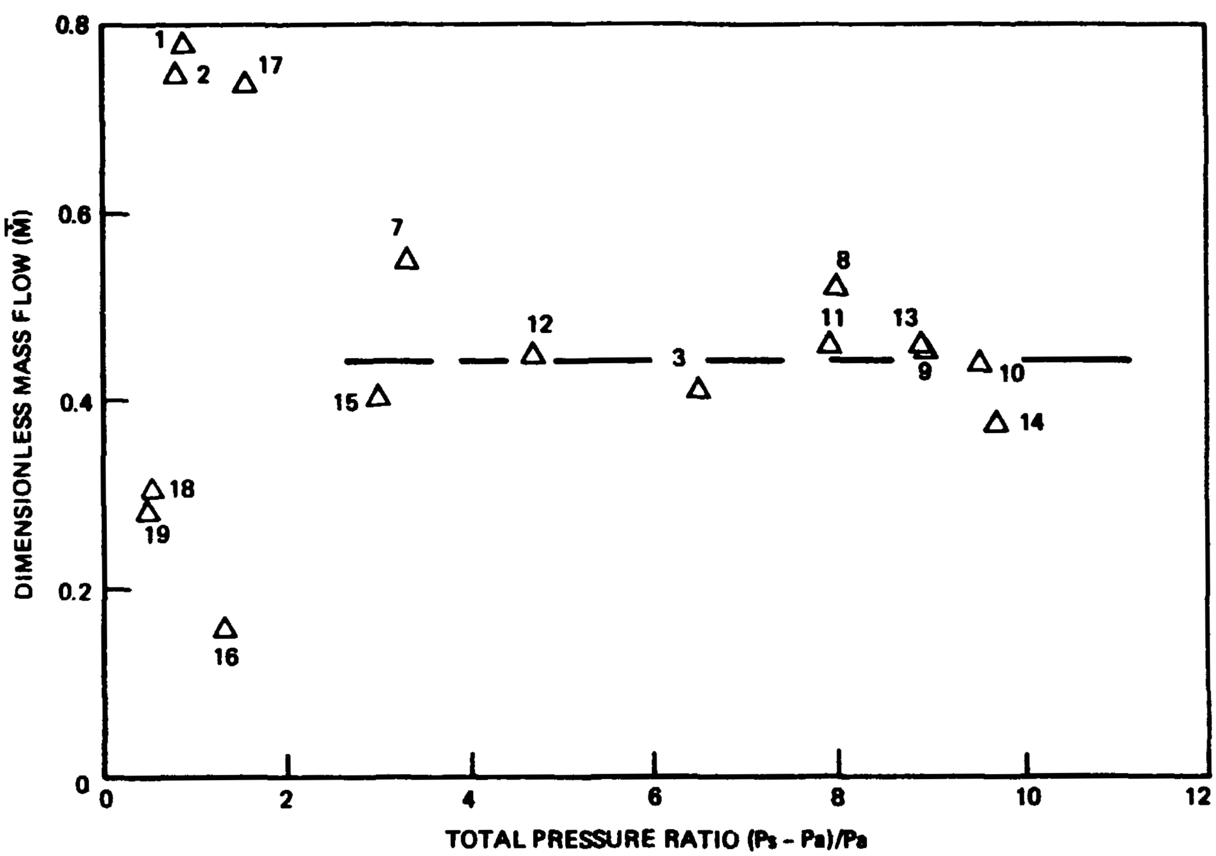

Figure 91. Hybrid Bearing Dimensionless Flowrate vs Overall Pressure Ratio

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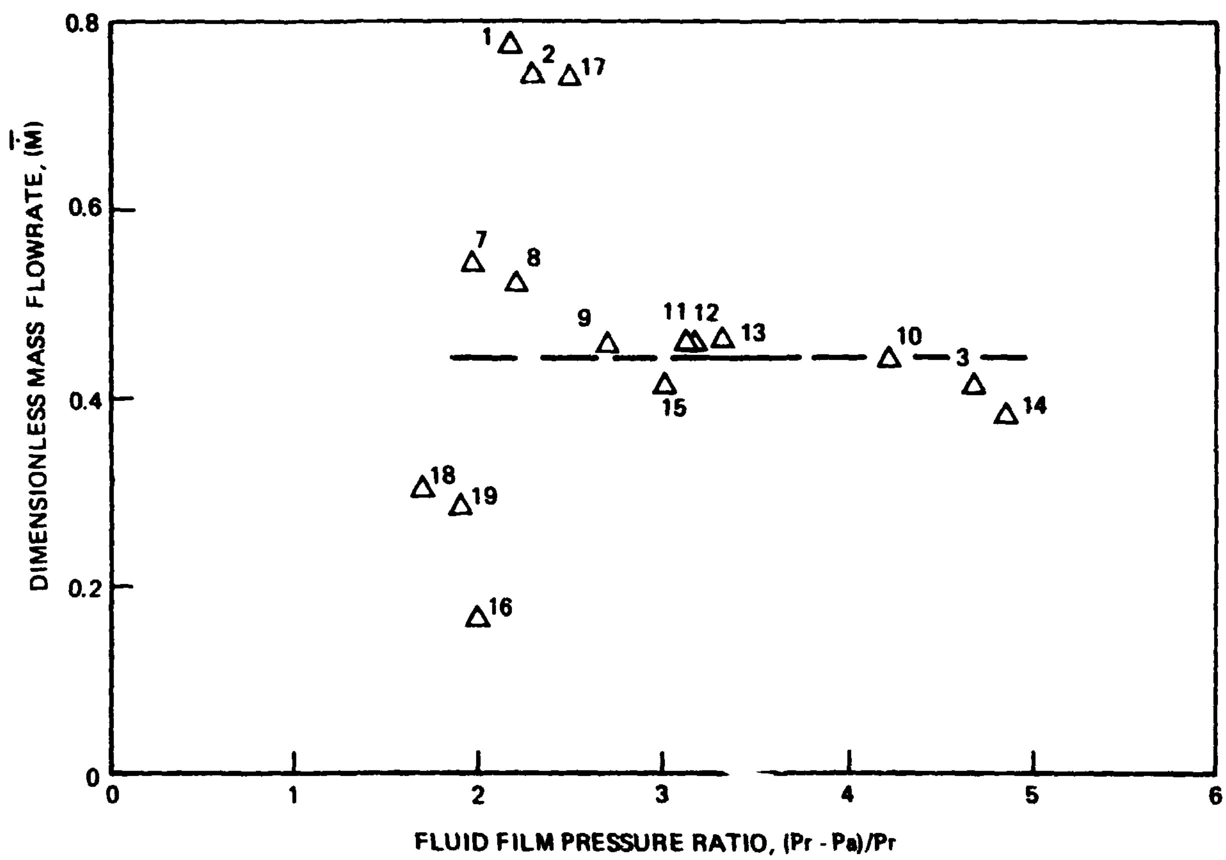

Figure 92. Hybrid Bearing Dimensionless Flowrate vs Fluid Film Pressure Ratio

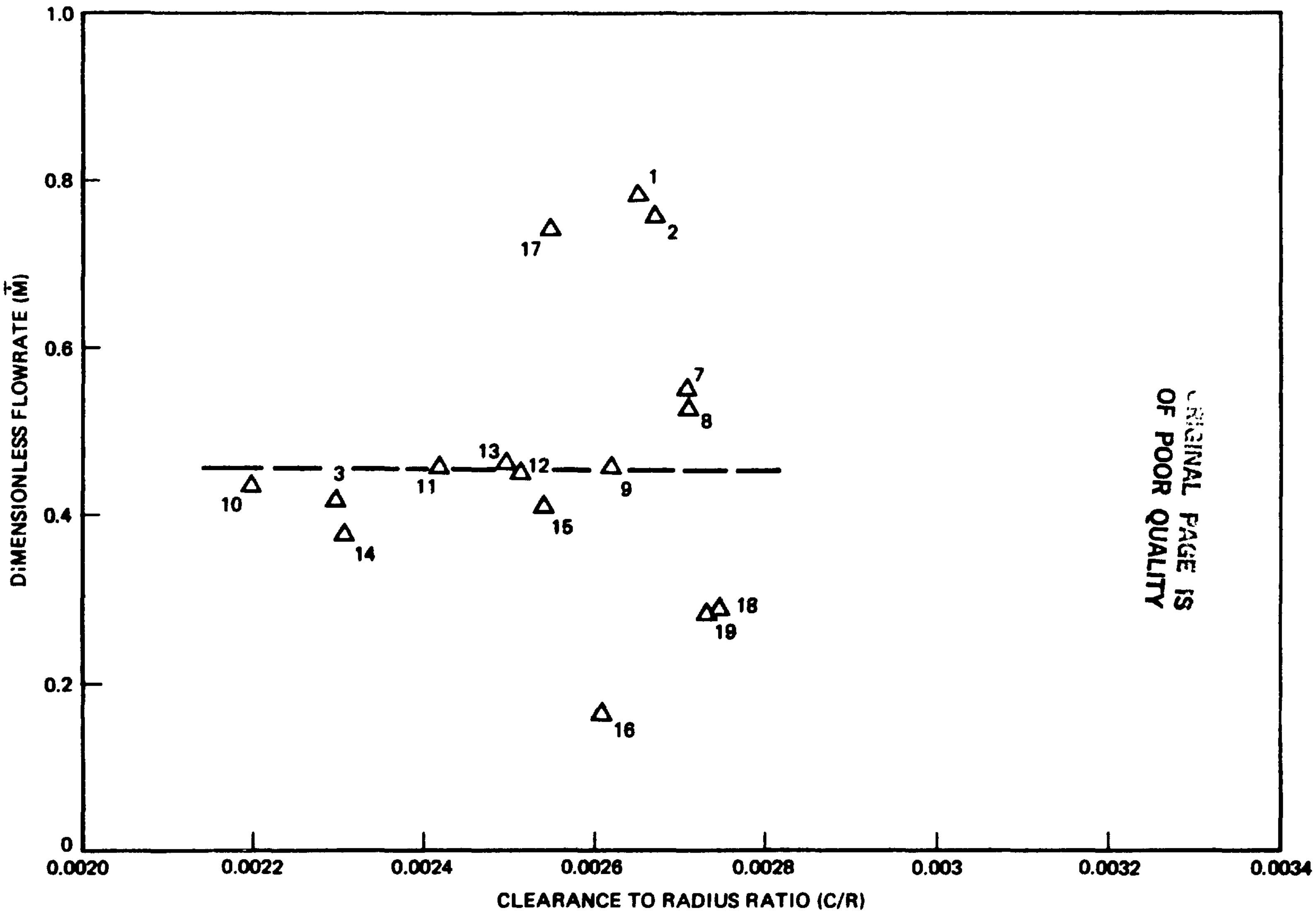

Figure 93. Hybrid Bearing Dimensionless Flowrate vs Clearance to Radius Ratio

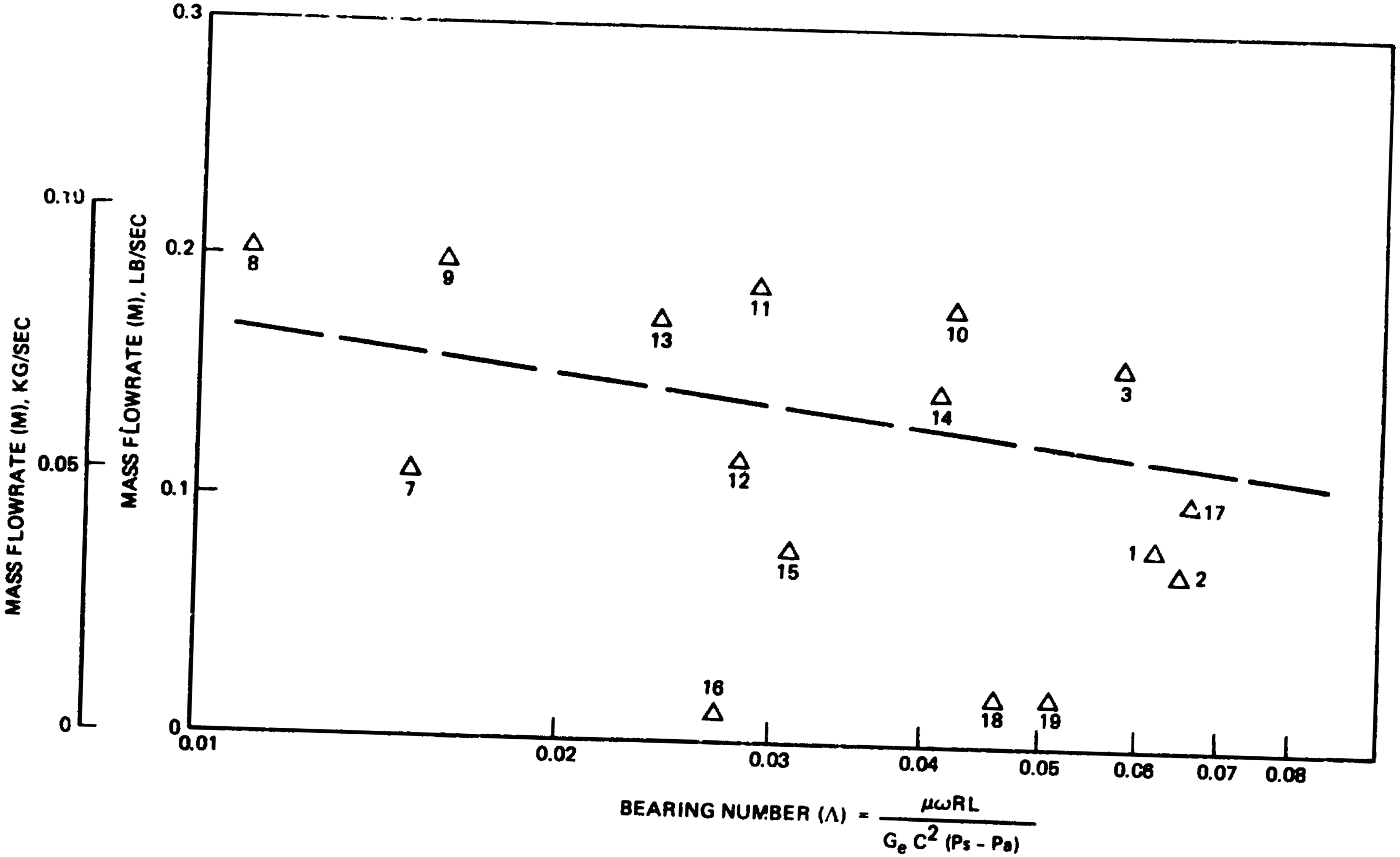

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Figure 94. Hybrid Bearing Mass Flowrate vs Bearing Number

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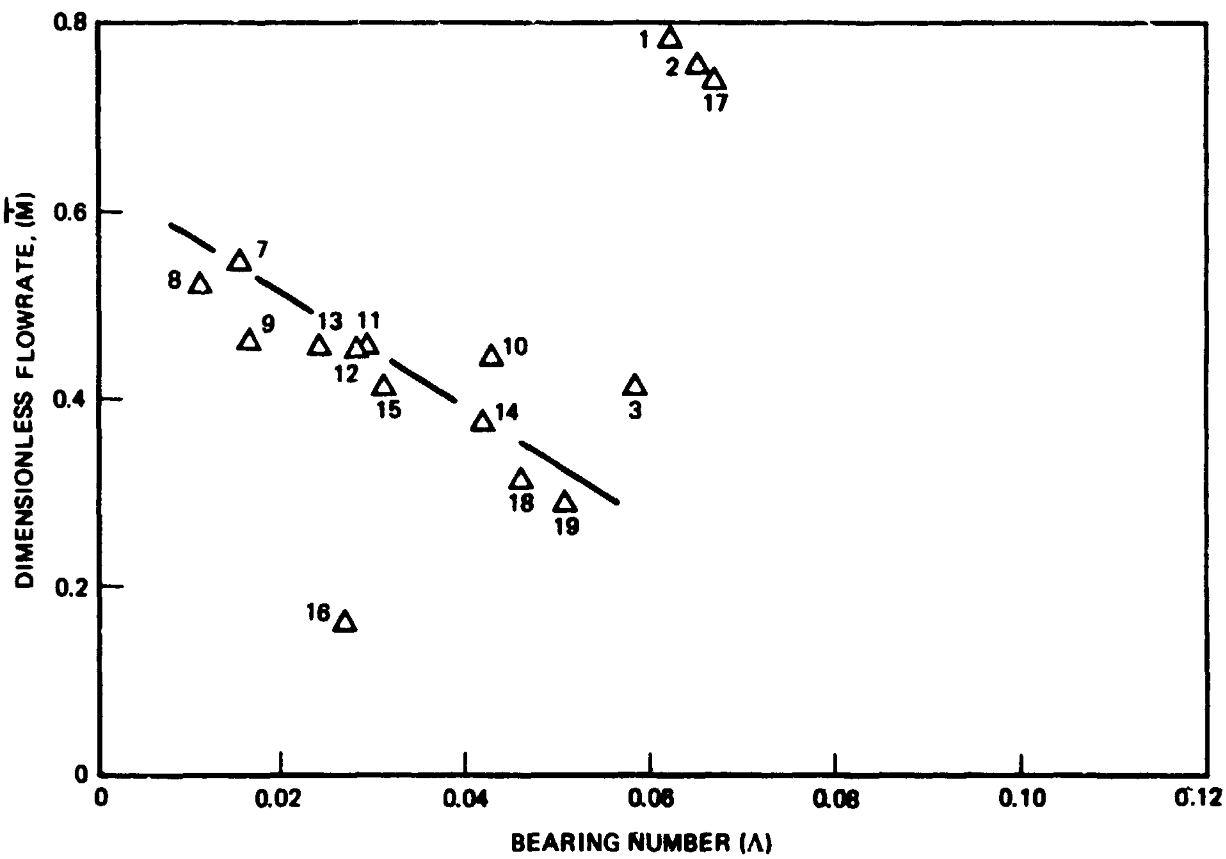

Figure 95. Hybrid Bearing Dimensionless Flowrate vs Bearing Number

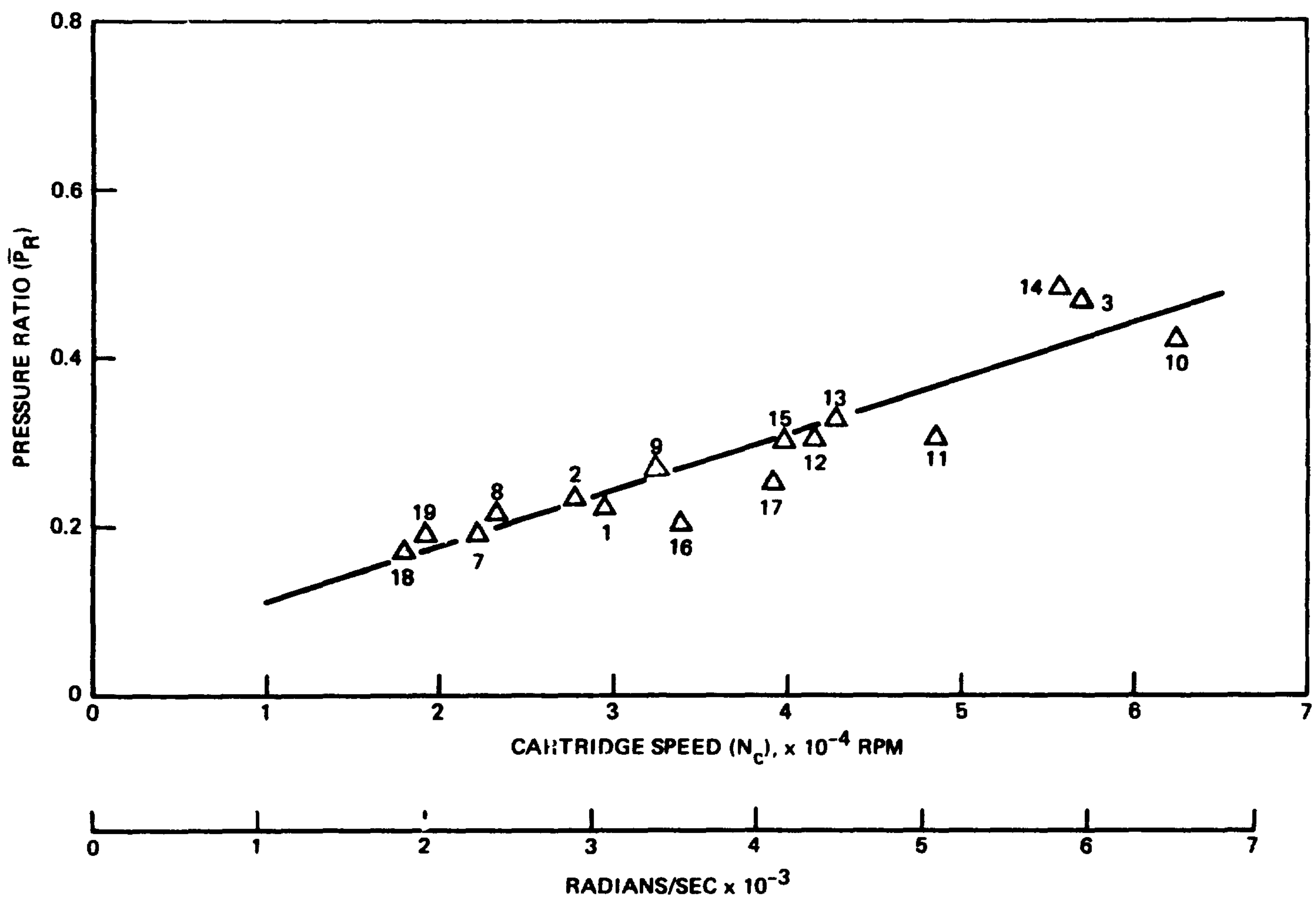

Figure 96. Hybrid Bearing Pressure Ratio vs Cartridge Speed

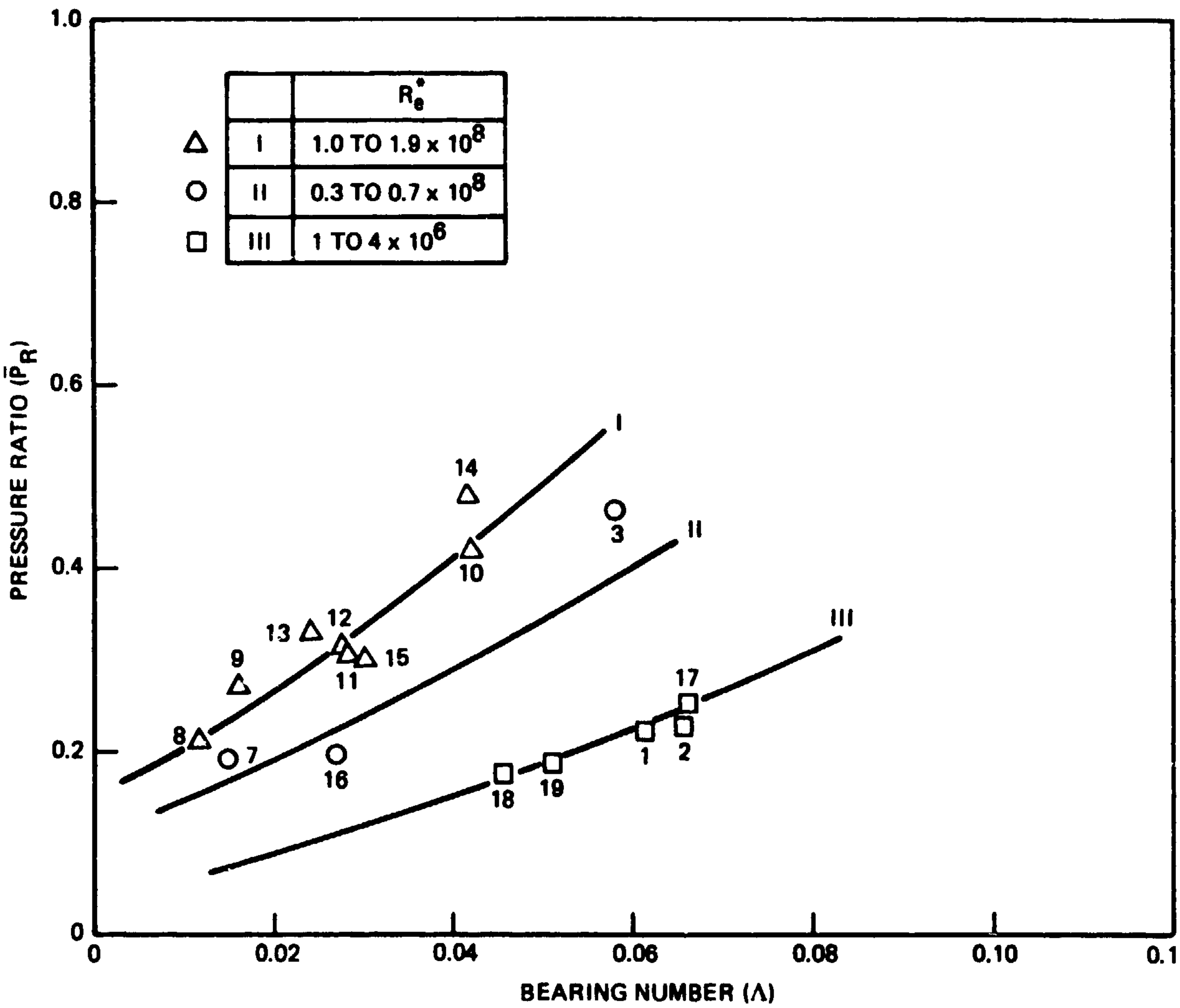

Figure 97. Hybrid Bearing Pressure Ratio vs Bearing Number

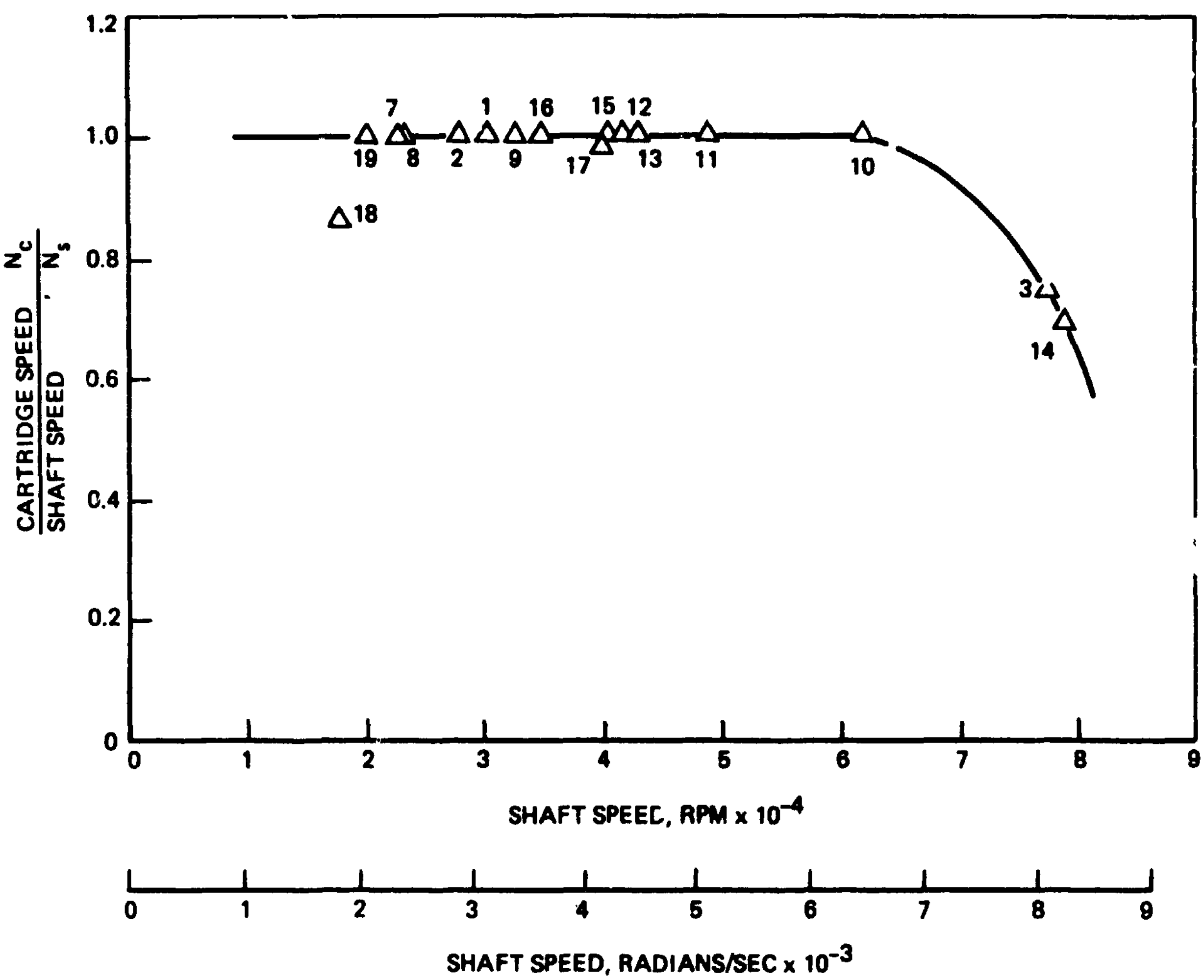

Figure 98. Cartridge-to-Shaft Speed Ratio vs Shaft Speed

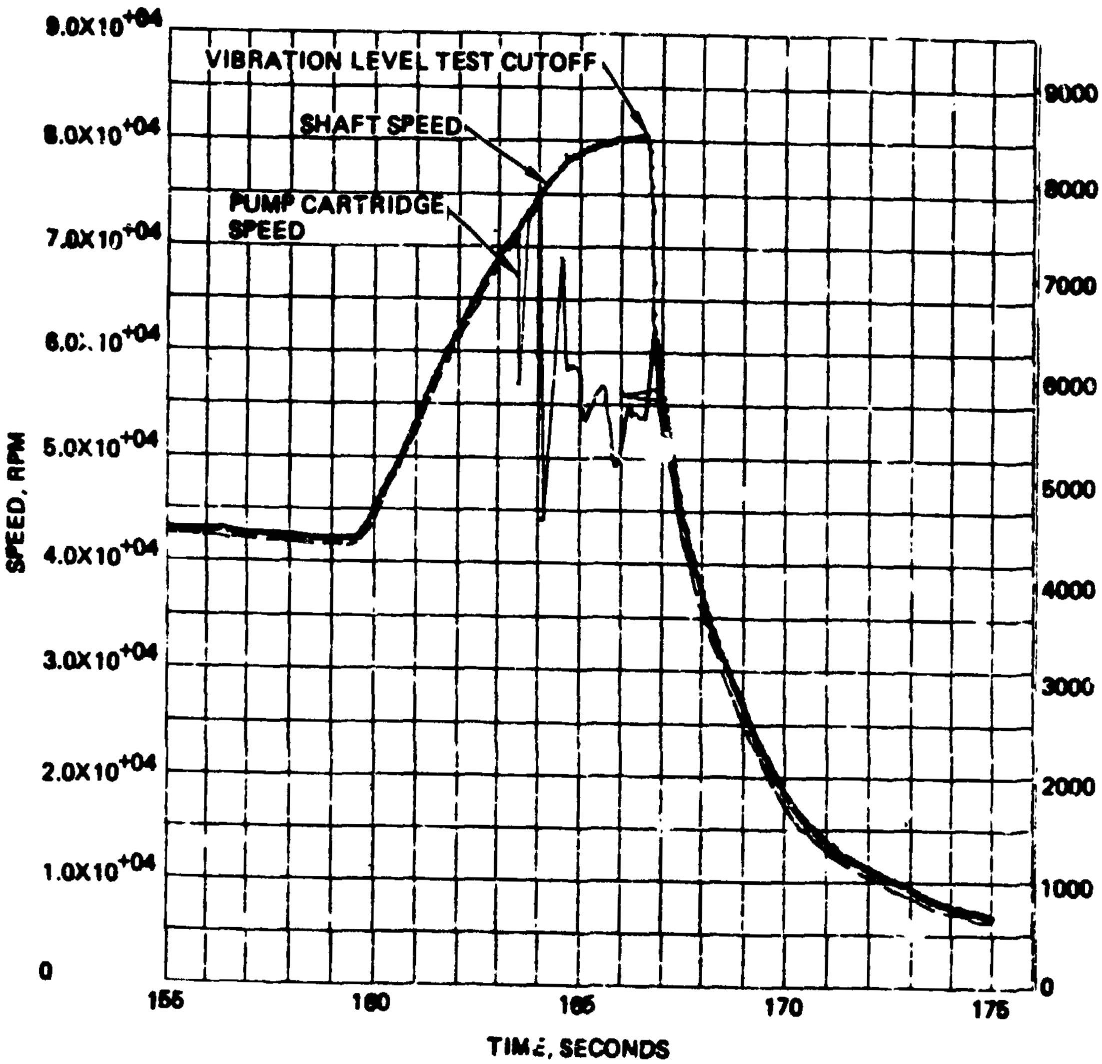

Figure 99. Pump-End Cartridge and Shaft Speed Data - Test 010

(400,000 lb/in. x 0.00202 in. ≅ 800 lbf). This large radial f e could result from the influence of the second critical speed 8378 radians/sec (80,000 rpm) as shown in the dynamics analysis of the turbopump tests. There was a high radial response of the Bently proximeter shaft position data. This part of the shaft is adjacent to the hydrostatic bearings. If the shaft response to this resonance is great enough to cause slight hydrostatic bearing contact, it would produce the speed lag as shown in Fig. 99. Once the hydrostatic bearing surface has been degraded, the film friction torque could be increased to surpass that ball bearing friction torque. Note that all bearing flow data after test point 010B/14 has more data scatter than the points prior to that test. This may also reflect the increased surface roughness of the bearing annulus. This speed lag is not considered to be due to the difference between the ball bearing and fluid film friction torque. Early calculations indicated that ball bearing friction torque is higher on the pump end bearing than the film friction torque at all speeds. The friction analysis of Fig. 88 is based on a condition of an aligned journal with the bearing. Shaft deflection data from the shaft proximeters would indicate that there is a great deal of shaft bow which has been indicated. The characteristic of the cartridge speed data of Test 014 (Fig. 100) indicates a combined set of forces. One of these forces is the frictional torque differences between the ball bearings and the fluid film which result in a threshold pump cartridge speed of approximately 6283 to 6702 radians/sec (60,000 to 64,000 rpm) for a shaft speed of 7749 to 8063 radians/sec (74,000 to 77,000 rpm). The other force is the slight intermittent contact of the journal with the bearing causing brief decelerations followed by recovery back to the threshold cartridge speed indicated. Recent analytical development of bearing operating characteristic indicate the concept of hybrid hydrostatic bearing threshold speeds is valid. This is due to torque differences between ball bearings and hydrostatic bearings as a function of shaft speed. Although the film friction is directly proportional to the fluid's viscosity, its direct influence on the speed ratio is indicated to be negligible within the operating viscosity range used in Mark 48 turbopump (Fig. 101). The main cause of the cartridge speed lag seen here is thought to be due to the vibration levels which cause intermittent contact.

Effects of Clearance. Besides the influence on flowrate, an increase in clearance lowers the film resistance as a result of less fluid shearing as illustrated in Fig. 102 and 103. The consequence of this reduction in film resistance is a decrease in pressure ratio $\bar{P}_R$. This is demonstrated in Fig. 104 and 105. Since the clearance decreases with speed increase and the fluid pressures available to the hydrostatic bearings increase, the operating $\bar{P}_R$ is generally small at low speed. One undesirable effect is the resultant reduced stiffness and radial load capacity at low speeds due to the reduced fluid film pressure drop at the low pressure ratio.

Subsynchronous Vibrations during Test 014. High subsynchronous vibration occurred prior to cutoff during Test 014. Figure 106 shows the relationship between the vibration levels at data points 1, 2, 3, 14, 17, and 18 and their squeeze numbers. Data point 1 and 2 corresponds to the first half of the Test 014 during which the shaft speed was t 3142 radians/sec (30,000 rpm). Relatively low vibration levels had been recorded up to this stage. The data point 3 (Test 014B/19) indicates a rapid rise in vibration when the shaft was accelerated to 8042 radians/sec (76,800 rpm). During this time the cartridge speed increased to only 5948 radians/sec (56,800 rpm), (Fig. 100). This occurred in Test 010B/14 (point 14) as well (Fig. 99).

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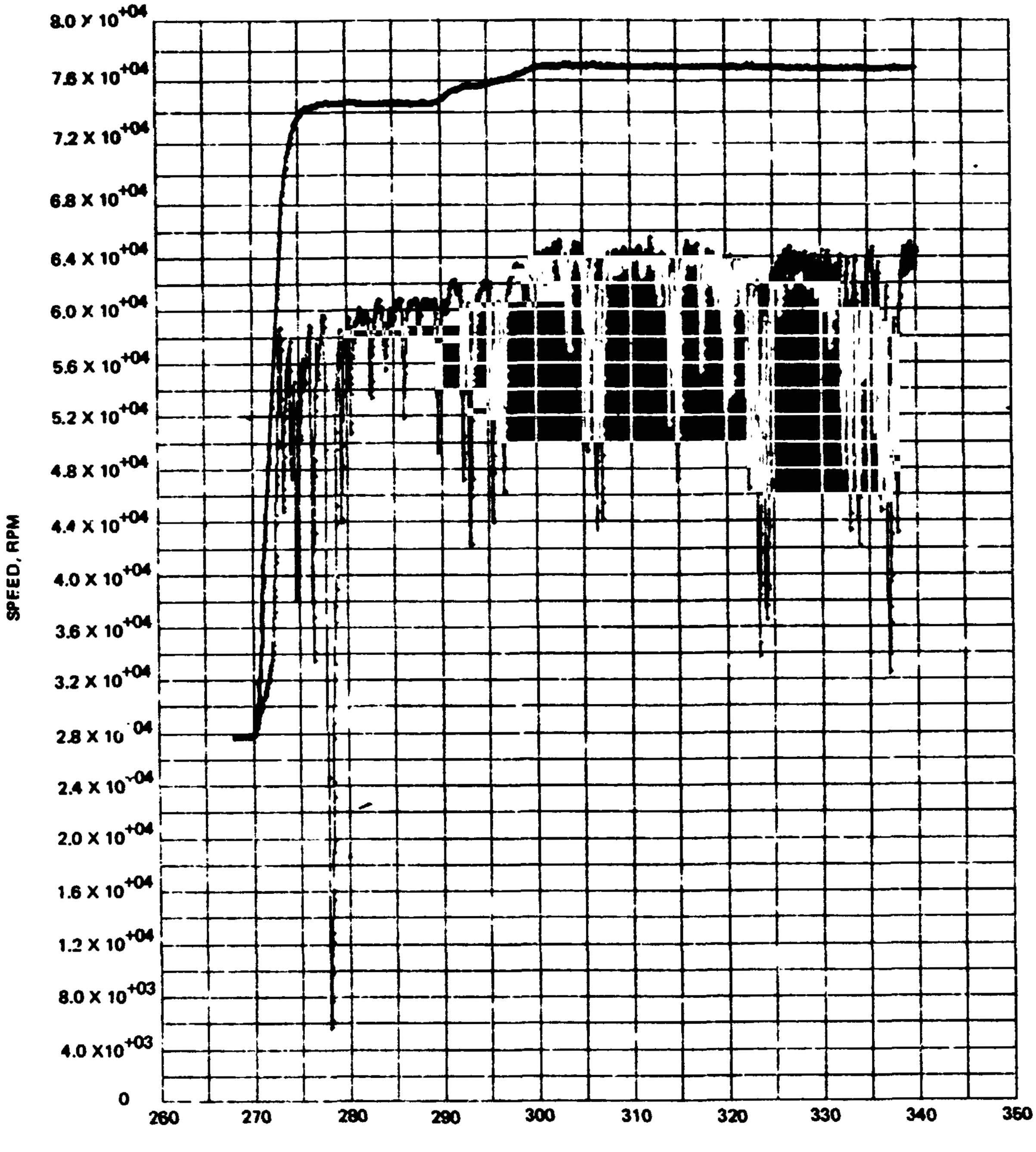

Figure 100. Pump-End Cartridge and Shaft Speed Data, Test 014

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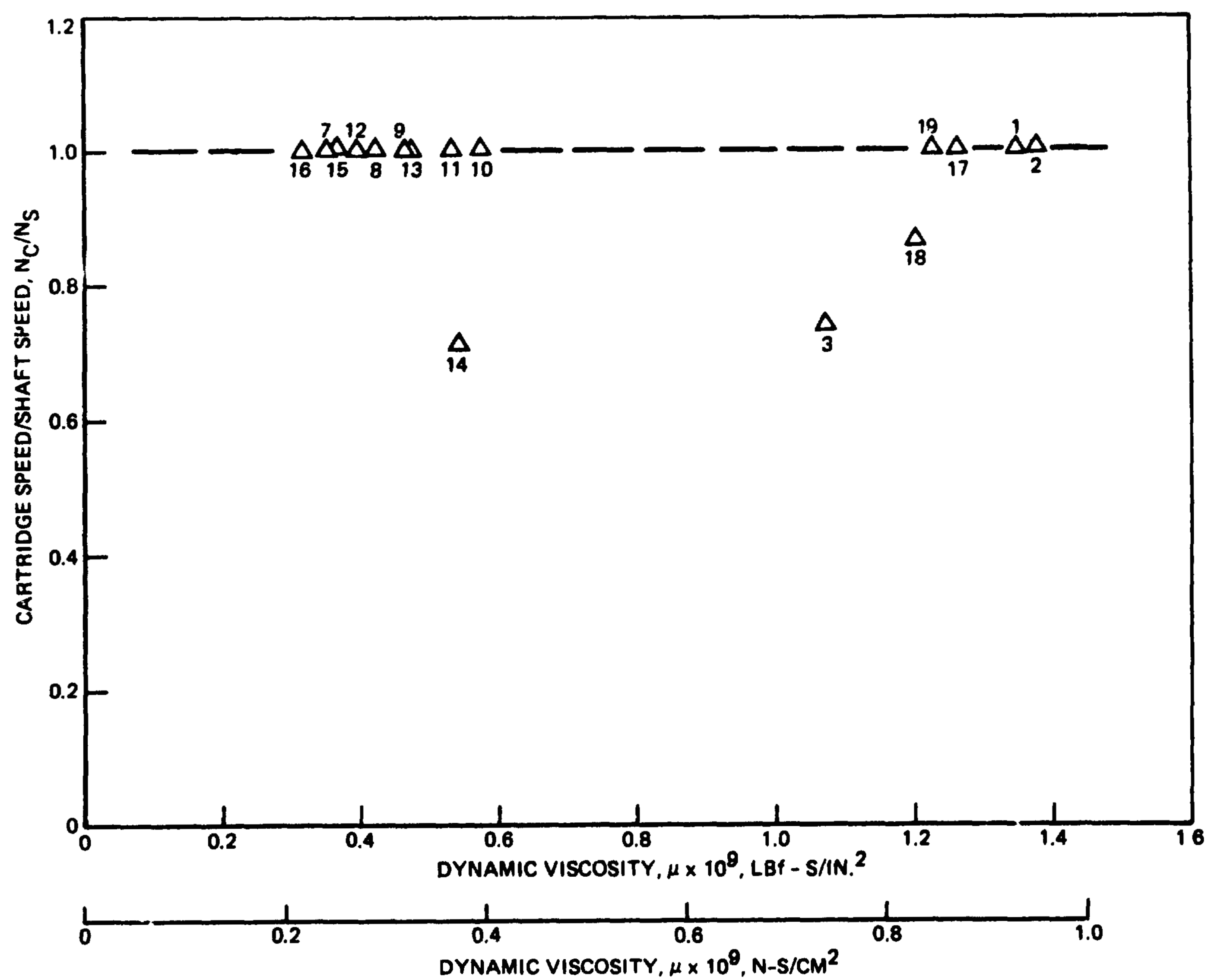

Figure 101. Cartridge-to-Shaft Speed Ratio vs Dynamic Viscosity

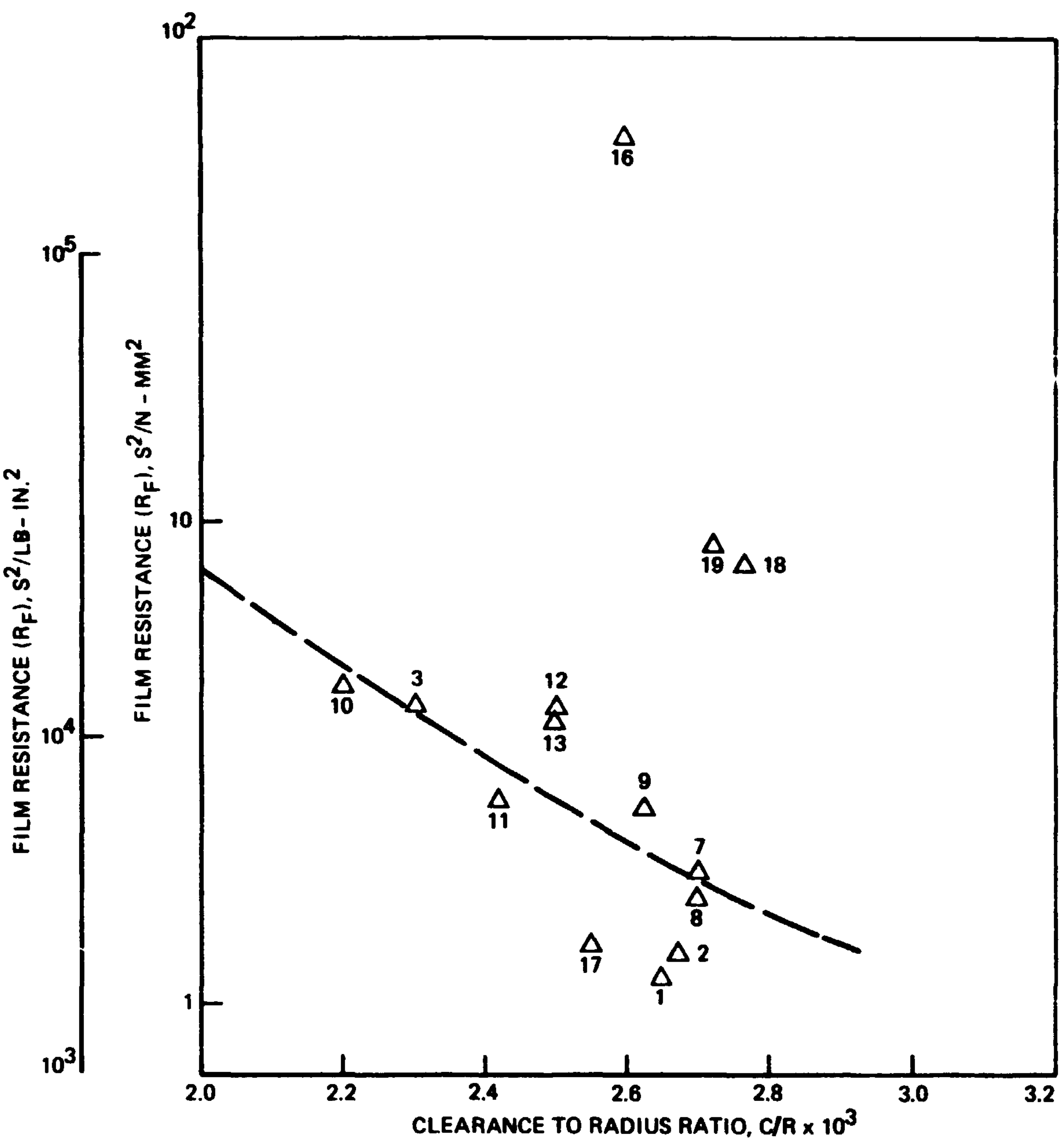

Figure 102. Hybrid Bearing Fluid Film Resistance vs Clearance to Radius Ratio

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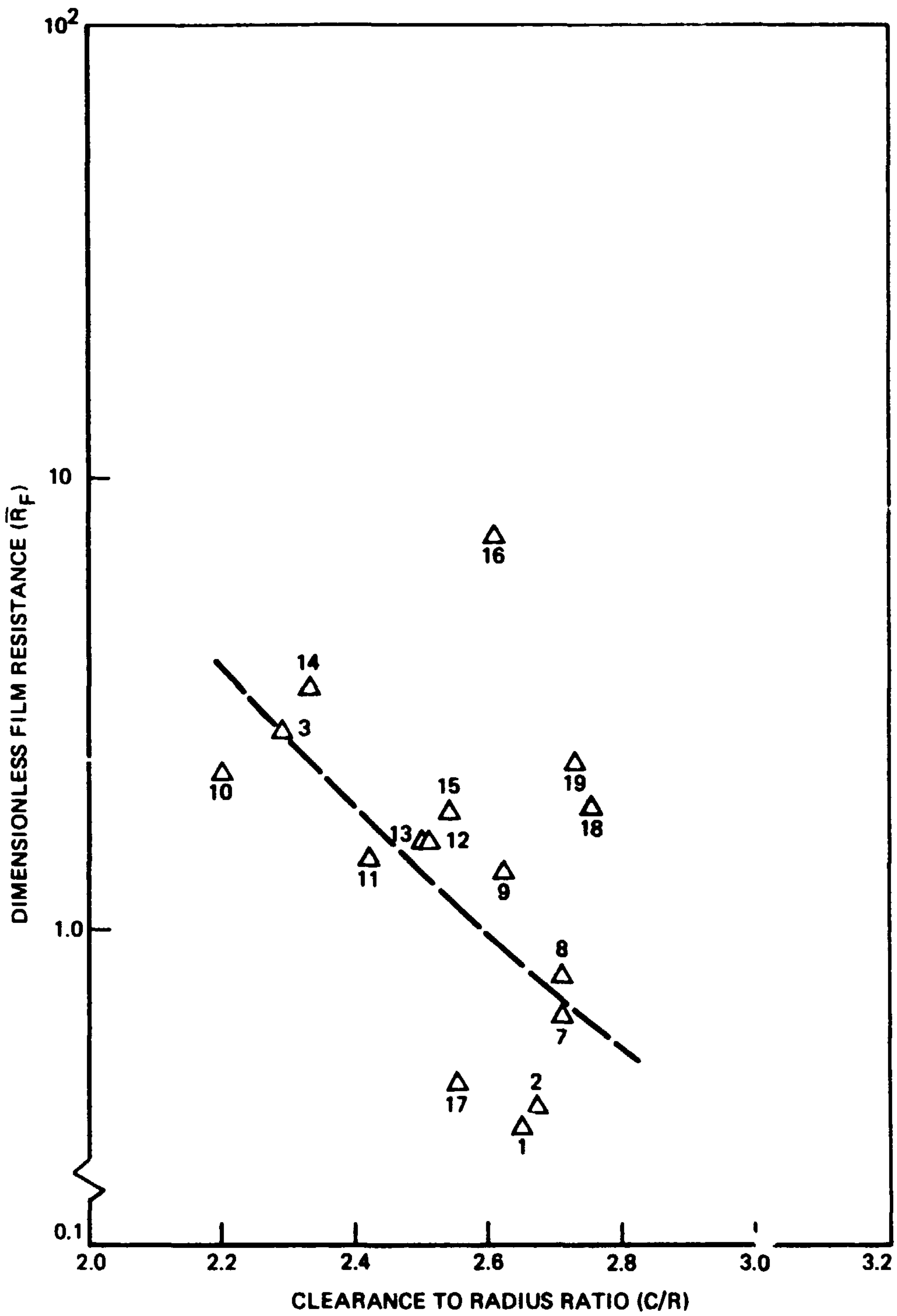

Figure 103. Dimensionless Fluid Film Resistance vs Clearance to Radius Ratio

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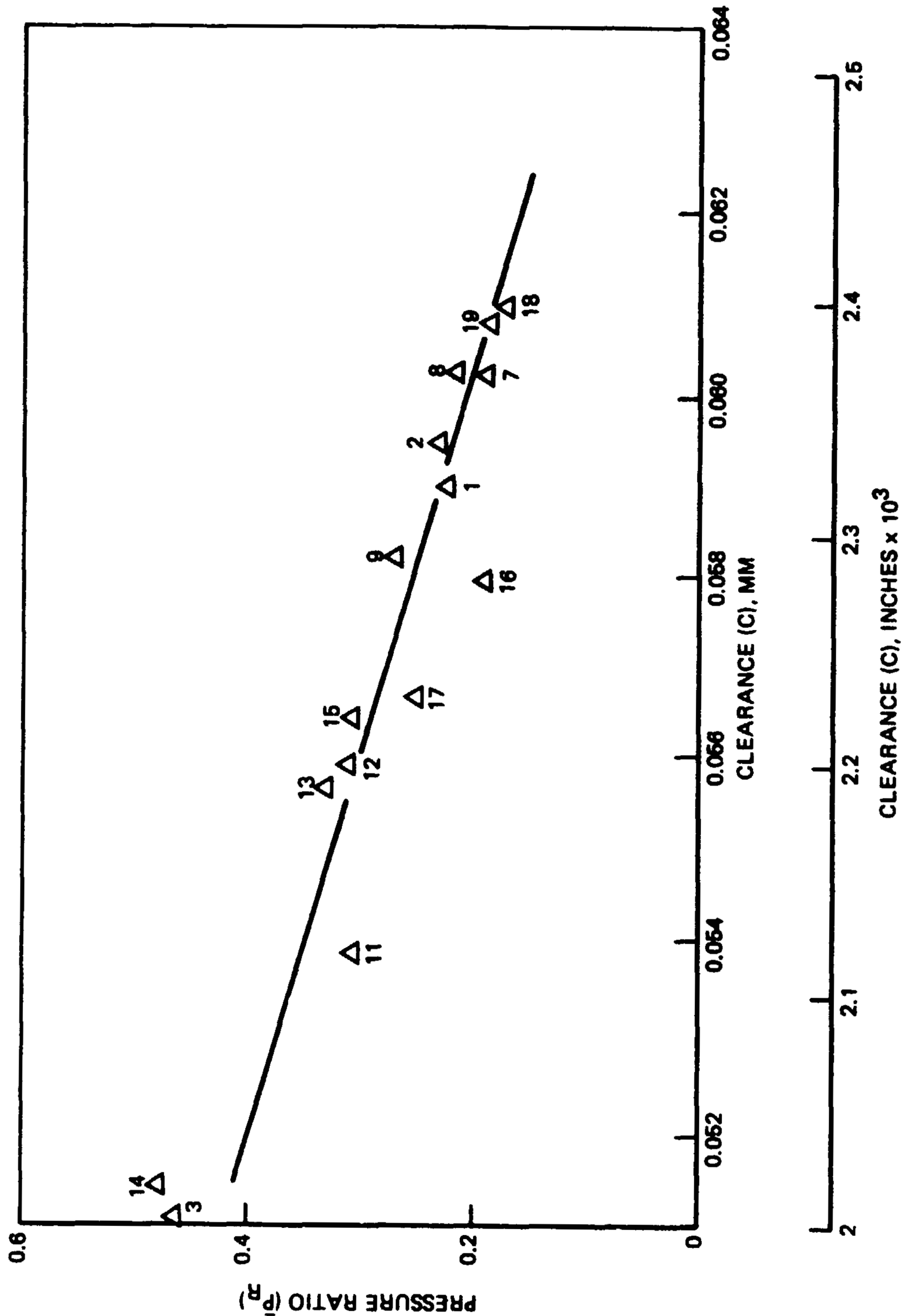

Figure 104. Hybrid Bearing Pressure Ratio vs Bearing Clearance

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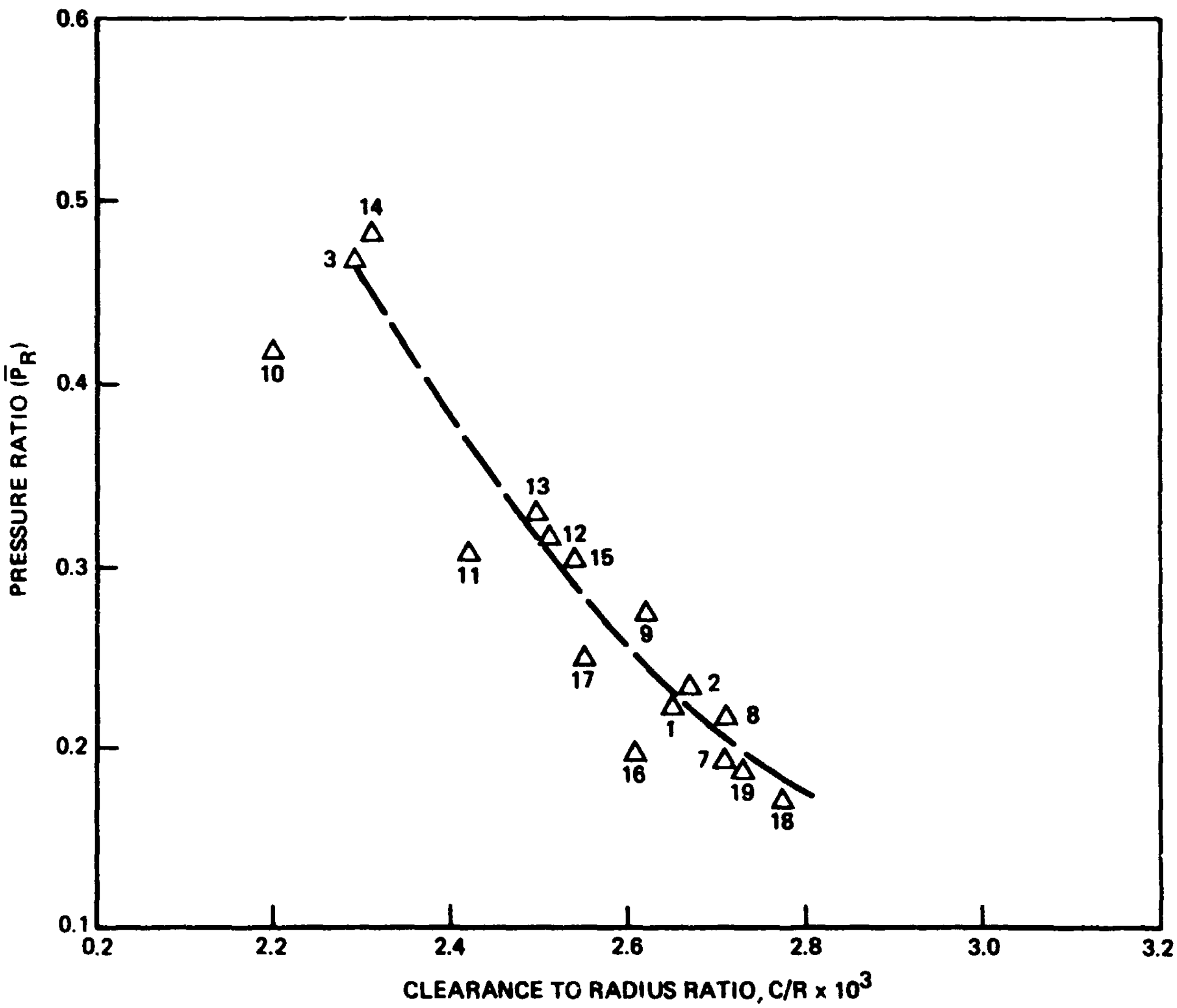

Figure 105. Fluid Film Pressure Ratio vs Clearance to Radius Ratio

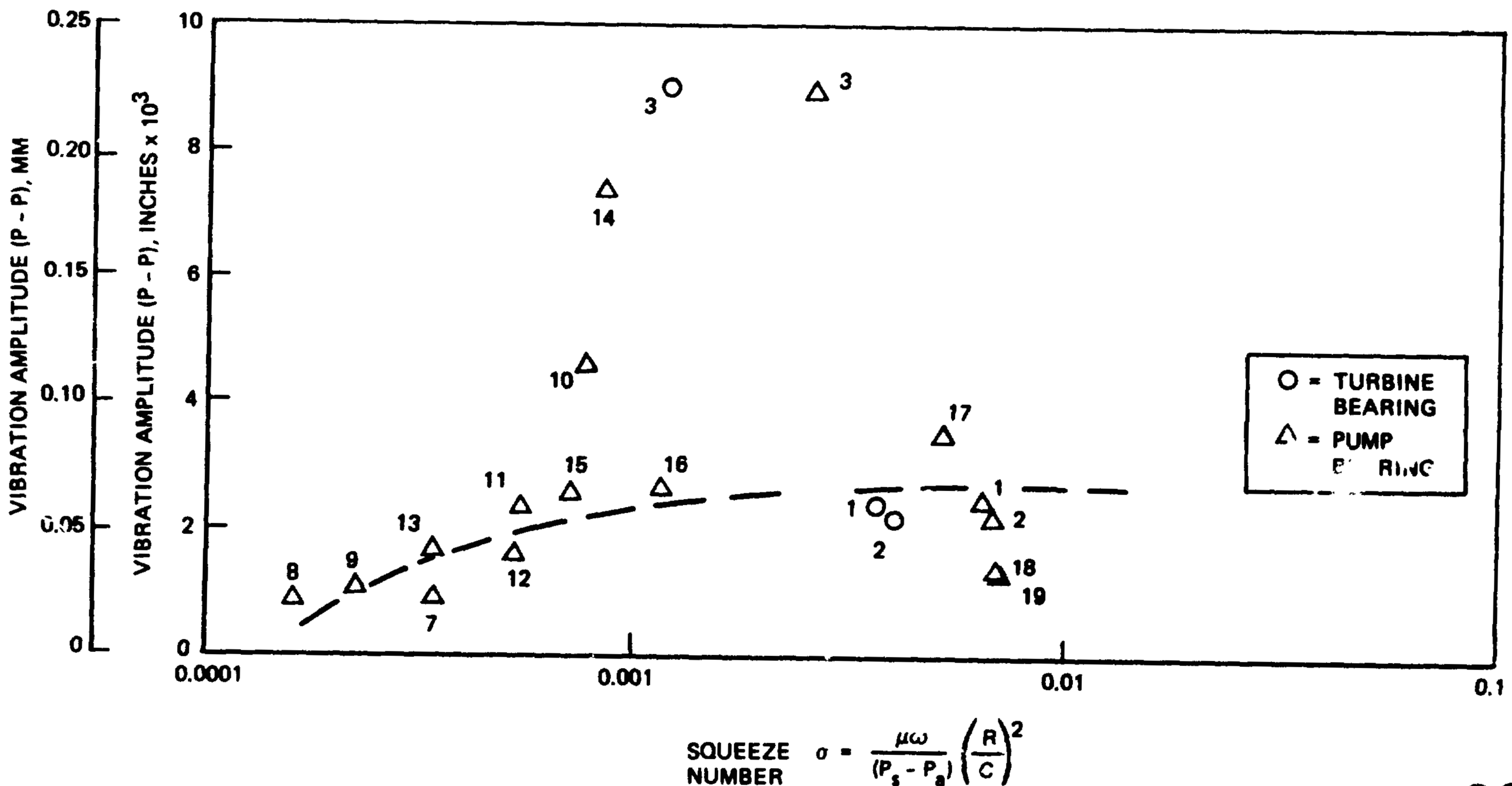

Figure 106. Vibration Amplitude vs Bearing Squeeze Number

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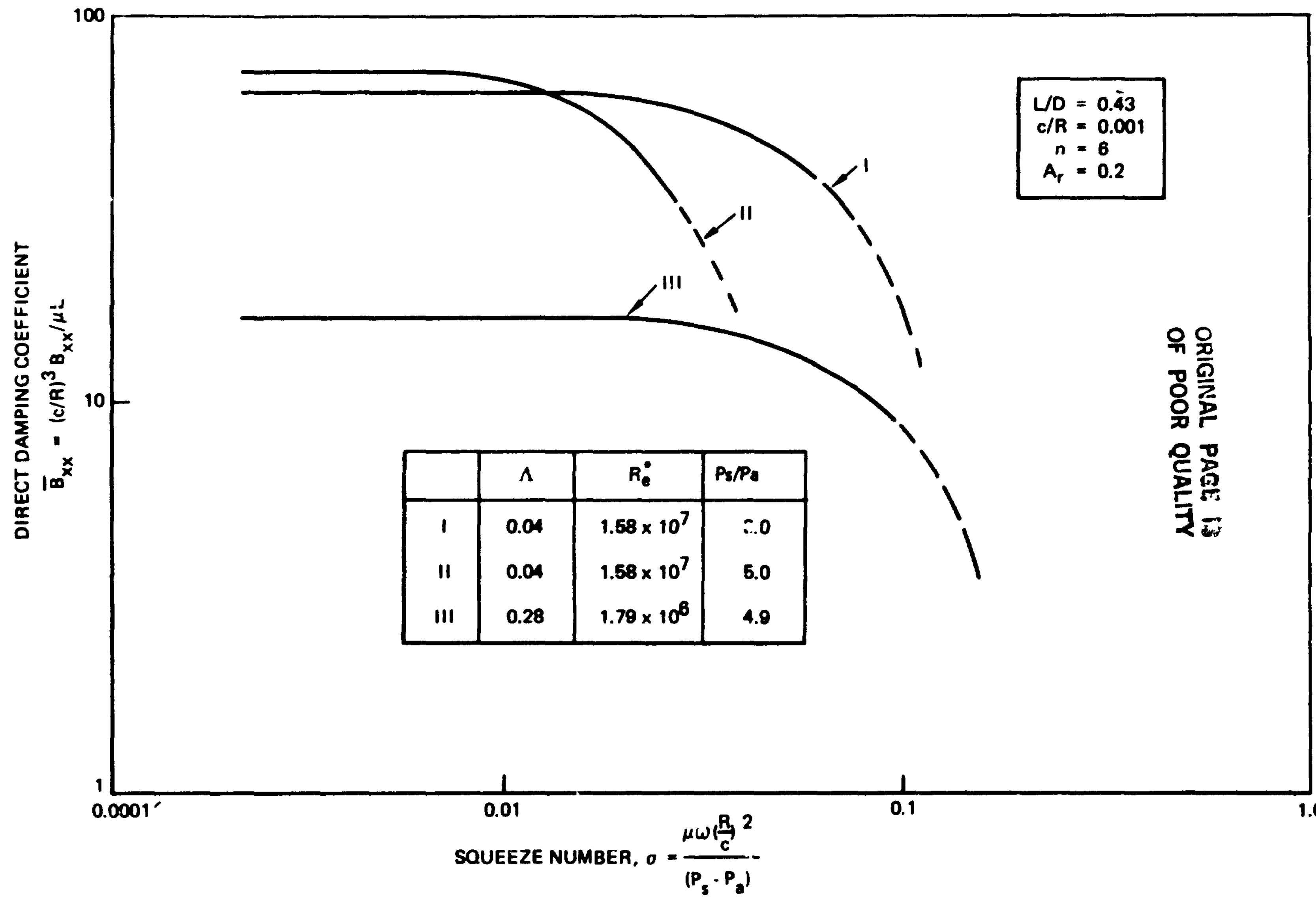
The physical significance of the squeeze number is the squeeze velocity at which the bearing moves radially onto the fluid film. This squeeze velocity is directly proportional to the vibration frequency; therefore, it represents the external excitation frequency which, in this case, is the shaft speed.

Theoretical analysis shows that there exists a threshold squeeze number beyond which the bearing damping ability breaks down, resulting in subsynchronous whirl (Fig. 107). The data indicate the tests conditions were well below that threshold number of 0.02. The shaft bearing system will be unstable whenever the system's lowest critical speed falls below this threshold frequency. The data shows that at the point of instability (test point 3) the squeeze number was at the mid range of all the test data (0.001 to 0.003). The shaft rpm was 76,827 for point 3 and 78,784 for point 14 which is approximately twice the first critical speed. All data above σ = 0.003 were at relatively low speeds where stability exists and less damping is required.

Figure 107 illustrates that the threshold squeeze number σ is approximately ≥ 0.02 from the theoretical analysis. The squeeze numbers, of the test data all fall well below 0.01 as shown in Fig. 106. A majority of the vibration levels were around 0.102 mm (0.004 inch p-p). The dotted line indicates the average vibration, and it shows a slight rise with increasing squeeze numbers. This is expected because the unbalance response of a rotor is proportional to the square of speed. At data point 3, the rotor experienced excessive vibration but the squeeze number is still very low (0.001 to 0.003). Therefore, it is very unlikely that this high vibration was the result of damping breakdown due to high squeeze action. That is not to say that the bearing damping alone was sufficient to prohibit subsynchronous whirl instabilities but that the net damping of the system was inadequate.

A probable cause of the hydrostatic bearing rubbing is proposed as follows. The turbopump was running at a steady speed of approximately 3142 radians/sec (30,000 rpm) for the first half of Test 014 and was accelerated to 8063 radians/sec (77,000 rpm) just before the data point 3. The vibration amplitude, which might arise from some residual unbalance, increased with the shaft speed resulting in a large shaft bow (tilt). The bearing is subjected to rubbing at its end if the tilt is excessive. If rubbing does occur, the cartridge will drop in speed resulting in lower stiffness, capacity and damping, which, in turn, aggravates the situation. Inspection of the posttest bearing revealed generally an all-around galling at the pump cartridge end, which confirmed the hypothesis that rubbing did occur as a result of excessive shaft bow.

A remedy to the tilt-induced rubbing may be to improve the moment resistance capacity of the hydrostatic bearing. This moment is proportional to the distance between row centers of the recesses and the bearing stiffness, assuming a two-row recess configuration is adopted. Increasing the L/D ratio will help a great deal, but on the other hand the maximum allowable tilt will be reduced. There seems to be an optimal L/D ratio which yields maximum moment resistance. Wider space between the rows of recesses also aids but may promote greater flowrate. Greater L/D ratio also causes higher friction. A better approach might be to use damping-type seals (straight smooth) in the turbopump between the bearings to achieve damping and resistance to shaft bow in concert with hydrostatic bearing damping.



	Λ	R_e^*	Ps/Pa
I	0.04	1.58×10^7	[illegible].0
II	0.04	1.58×10^7	5.0
III	0.28	1.79×10^6	4.9

Figure 107. Predicted Direct Damping Coefficient vs Bearing Squeeze Number

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Empirical Correlation of Hydrostatic Bearing Flowrate

Additional empirical correlation of the hydrostatic bearing test flowrate data with the predicted data was used to improve the analytical model. This was done after testing. The results are discussed below.

Journal bearings can be divided into two classifications: (1) bearings where load-carrying capacity depends on an external pressure source and (2) bearings that derive load capacity from the pressure buildup within the fluid film. The first classification is usually referred to as hydrostatic bearings. For example, the Mark 48 fuel pump hydrostatic bearing is among this classification. The second classification is always referred to as hydrodynamic bearings which require relative motion of the bearing surfaces and eccentricity of the journal to build up the load capacity. In general, for a hydrostatic bearing, the rotation induced pressure (or circumferential flow) is much less than the external pressure-induced force (or axial flow). On the other hand, for the hydrodynamic bearing the rotation-induced force is dominant, and the hydrostatic effects are negligible.

In the last decade, turbomachinery design has evolved to require high-speed and low-clearance operation. As a result, the rotation and bearing surface roughness effects become important. The objective of this area of investigation was to check the surface roughness effect of the model developed in Ref. 5 and used to predict hybrid bearing flowrates. The check was made to determine the degree of rotation and surface roughness effects on the performance of the journal bearings or seals. The available Rocketdyne Mark 48 fuel turbopump test data and NASA hybrid bearing tester data base was used to check the model. Two major bearing performance parameters were investigated: the bearing leakage rate and the bearing dynamic coefficient.

Mass Flowrate prediction Improvements. In 1962, Yutaka Yamada (Ref. 6 and 7) analyzed experimentally the resistance of water flow through coaxial cylinders when the inner cylinder rotates. The following empirical formula for the friction coefficient was developed as presented by Ref. 8 and 11.

$$\frac{f_R}{4} = \underbrace{0.079\, R_a^{-0.25}}_{\text{Part I}} \underbrace{\left[1 + \left(\frac{7}{8}\frac{R_r}{R_a}\right)^2\right]^{3/8}}_{\text{Part II}} \tag{1}$$

where R_a is the axial flow Reynolds number, and R_r is the rotational Reynolds number. The first part of Eq. 1 is very close to the smooth pipe friction coefficient in the Moody diagram (Fig. 108) presented in many publications (e.g., Ref. 8). The second part is the correction of the friction coefficient due to rotation effects. Equation 1 was used directly by Black and Jenssen (Ref. 9 and 10) and later by Childs (Ref. 11 and 12) for seal friction coefficient calculations.

The R_a in Eq. 1 is defined as:

$$R_a = \frac{U_a \times 2 \times C \times \rho}{\mu} \tag{2}$$

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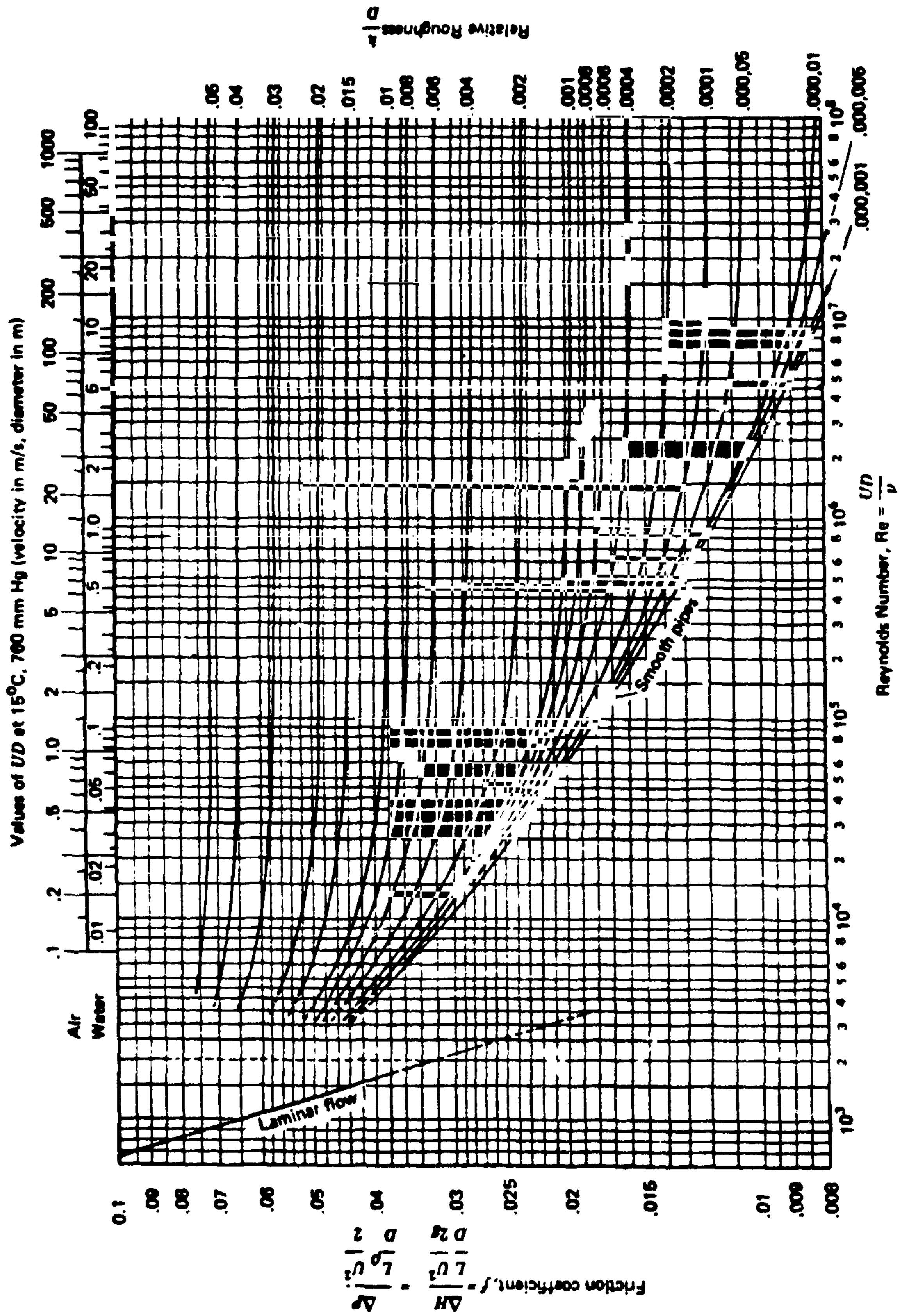

Figure 108. Moody Diagram

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If one uses Yamada's definition for R_a which is

$$R_a = \frac{U_a \times C \times \rho}{\mu} \tag{3}$$

Then Eq. 1 becomes

$$\frac{f_R}{4} = 0.26\ R_a^{-0.24} \left[1 + (7/8)^2 \left(\frac{R_r}{2R_a}\right)^2\right]^{0.38} \tag{4}$$

where Eq. 4 was the original equation presented by Yamada.

Yamada's equation is valid only for small values of relative roughness k/D (Fig. 108), where k is the surface finish and D is the hydraulic diameter. For most seals or hydrostatic bearings the clearance is relatively small, even for a very smooth surface finish, say 0.000406 mm (0.000016 inch). The relative roughness for a radial clearance of 0.0381 mm (0.0015 inch) is still about 0.005 instead of 0.0008 which is the perfectly smooth surface assumption.

As the Reynolds number or surface roughness increases or the clearance decreases, the error of the smooth surface assumption is magnified. To account for both the surface roughness effects and rotational effects, a semi-emperical formula based on Yamada's equation and the Moody diagram has been developed within the hydrostatic bearing analysis computer code previously mentioned (Ref. 5) and consistently used by Rocketdyne for seal friction coefficient calculations.

Table 12 and Table 13 represent the Rocketdyne bearing test data (pump side) and the comparison between measured data with various methods of prediction. The cartridge rotational speed rpm, mass flowrate $\dot{m}$, fluid density ρ, and fluid dynamic viscosity μ were obtained directly from test data, while the radial clearance C is based on the stress analysis presented in Ref. 13. The axial velocity U_a, circumferential velocity U_r, axial Reynolds number R_a, circumferential Reynolds number R_r, the friction coefficient without rotation f, the friction coefficient with rotation f_R and the percentage of rotation effect on the friction coefficient $\Delta f_{\%}$ were calculated by the following equations:

$$U_a = \frac{\frac{\dot{m}}{\rho}}{\pi \times D \times C \times 2\ g} \tag{5}$$

where the diameter of the cartridge D for this case is equal to 4.445 cm (1.75 inches)

$$U_r = \frac{D}{2} \times \omega \tag{6}$$

TABLE 12. ROCKETDYNE MARK48-F HYDROSTATIC BEARING TEST DATA

(S.I. UNITS)

TEST/ SLICE NO.	CARTRIDGE SPEED, RAD/S	C, MM	$\dot{M}$, KG/S	ρ, KG/M3	μ, N/M-S	U_A, M/S	U_R, M/S	R_A	R_R	F	F_R	ΔF, %	F'
008A/22	3407	0.0582	0.0901	52.684	30.6×10^{-6}	105	75.5	2.0×10^{5}	7.4×10^{4}	0.0149	0.0154	3.8	0.058
010A/7	4468	0.0556	0.0833	46.169	32.1×10^{-6}	116	99.3	1.82×10^{5}	7.8×10^{4}	0.0153	0.0160	5.0	0.0588
014B/16	6461	0.0490	0.0717	64.716	73.0×10^{-6}	80.8	143	6.9×10^{4}	6.1×10^{4}	0.0195	0.0232	19.2	0.0715
008B/4	6528	0.0485	0.0823	53.775	38.96×10^{-6}	113	145	1.5×10^{5}	9.5×10^{4}	0.0160	0.0176	10.5	0.063

(ENGLISH UNITS)

TEST/ SLICE NO.	RPM CARTRIDGE	C, INCH	$\dot{M}$, $\frac{LBM}{SEC}$	ρ, $\frac{LBM}{F^3}$	μ, $\frac{LBM}{F\text{-}SEC}$	U_A, FPS	U_R, FPS	R_A	R_R	F	F_R	ΔF, %	F'
008A/22	32,532	0.00229	0.1986	3.2889	2.1×10^{-6}	345	248	$2.0\ 10^{5}$	7.4×10^{4}	0.0149	0.0154	3.8	0.058
010A/7	42,663	0.00219	0.1836	2 8822	2.2×10^{-6}	381	326	1.82×10^{5}	7.8×10^{4}	0.0153	0.0160	5.0	0.0588
014B/16	61,701	0.00193	0.1581	4.04	5.0×10^{-6}	265.5	471	6.9×10^{4}	6.1×10^{4}	0.0195	0.0232	19.2	0.0715
008B/4	62,338	0.00191	0.1815	3.357	2.67×10^{-6}	370.7	476	1.5×10^{5}	9.5×10^{4}	0.016	0.0176	10.5	0.063

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TABLE 13. COMPARISON BETWEEN ROCKETDYNE MEASURED DATA AND PREDICTION

(S.I. UNITS)

TEST/ SLICE NO.	MEASURED $\Delta P, N/CM^2$	PREDICTED WITH F		PREDICTED WITH F_R		PREDICTED WITH F'	
		$\Delta P, N/CM^2$	% ERROR	$\Delta P, N/CM^2$	% ERROR	$\Delta P, N/CM^2$	% ERROR
008A/72	192	81	57	83	56	191	0.5
010A/7	226	90	60	92	59	214	5.6
014B/16	211	74	65	83	61	189	10.4
008B/4	290	109	62	114	60	278	4.3

(ENGLISH UNIT)

TEST/ SLICE NO.	MEASURED ΔP, PSI	PREDICTED WITH F		PREDICTED WITH F_R		PREDICTED WITH F'	
		ΔP, PSI	%ERROR	ΔP, PSI	% ERROR	ΔP, PSI	% ERROR
008A/72	278.3	118	57	120	56	277	0.5
010A/7	328.4	131	60	134	59	310	5.6
014B/16	306	108	65	120	61	274	10.4
008B/4	421	158	62	166	60	403	4.3

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where U_r is the rotational speed

$$R_a = \frac{U_a \times 2 \times C \times \rho}{\mu} \tag{2}$$

If R_a is calculated by Eq. 2 instead of Eq. 3, then Eq. 1 should be used for the friction coefficient calculation:

$$R_r = \frac{U_r \times C \times \rho}{\mu} \tag{7}$$

$$f = 4 \times 0.079 \times R_a^{-0.25} \tag{8}$$

$$f_R = 4 \times 0.079 \times R_a^{-0.25} \left[1 + \left(\frac{7}{8}\frac{R_r}{R_a}\right)^2\right]^{3/8} \tag{9}$$

$$\Delta f_{\%} = \left(\frac{f_R - f}{f}\right) \times 100\% \tag{10}$$

As mentioned before, the values for f_R obtained from Eq. 9 take into account rotational effects but not surface roughness effects. Based on Ref. 5, using the Moody diagram (Fig. 108), the value f_R was modified to produce a new parameter f' which includes the effects of surface roughness. To calculate f, the bearing surface roughness was set to 0.00325 mm (0.000128 inch). The value of 0.00325 mm (0.000128 inch) surface roughness used for Mark 48 bearing and NASA hybrid tester correlation was determined by analysis of the Rocketdyne test data. This was slightly higher than the smooth part of the actual hardware. However, due to the existence of the hydrostatic pad (20 pads for this case), which contributes a roughness effect, the 0.00325 mm (0.000128 inch) effective surface roughness for this particular bearing was used. It is very difficult to predict the effective surface roughness for the bearing because the value depends on the number of pads and the flow passage interruptions. To determine the effective surface roughness, a tester can be developed, and the effective surface rougness can be obtained by precisely measuring the leakage rate, clearance and the pressure drop across the tester. The pressure drop across the film (pad-to-sump) was determined by:

$$\Delta P_{PREDICTION} = \left(K_{in} + K_{out} + \frac{FL}{D}\right)\left(\frac{\rho\, U_a^2}{2g \times 144}\right) \tag{11}$$

where the hydraulic diameter D equals 2 times the radial clearance.

The value of F can be defined by f, f_R, or f'. The entrance loss coefficient K_{in} was set to 0.5 and the exit loss coefficient K_{out} was set to 1.0. The characteristic friction length L* was approximated by the average fluid travel distance in axial direction and estimated with:

$$L^* = \frac{L - n \times L_P}{2} \tag{12}$$

where L and Lp are the axial bearing and pad length and n is the number of pad rows. In this case L equalled 1 inch, Lp was about 0.1 inch and n was equal to two. Therefore, the L value used for Eq. 11 was equal to 0.4 inch. Equation 12 is a good approximation for low values for n and especially good for n equals one. The predicted pressure drop based on: (1) the friction coefficient f without rotation, (2) the friction coefficient f_R with rotation, and (3) the friction coefficient f' with rotation and surface roughness effects included were tabulated in Table 13 for comparison with measured pressure drop.

Table 12 indicates that the rotational effect on the friction coefficient is less than 20%. However, the surface roughness effects could increase the friction coefficient by a factor of 3. As indicated in Table 13, without the surface roughness effects included the predicted pressure drop with or without rotational effects is underestimated by 60%. With the surface roughness effects included, the difference between prediction and data is less than 15%. The reason for this significant improvement is readily explained by the Moody diagram (Fig. 108). At Reynolds number close to 10^5, which is close to the Mark 48 pump operational range, with radial clearance in the range of 0.0508 mm (0.002 inch) and surface roughness equal to 0.00325 mm (0.000128 inch), the friction coefficient should be 0.06, which is more than 3 times bigger than the value for the smooth surface assumption. Similar calculations have been carried out for the available NASA test data and are summarized in Tables 14 and 15. The NASA hybrid tester radial clearance curve (as shown in Fig. 109) was obtained from Ref. 14. Speed, flowrate, density, and viscosity were provided by Mr. Hannum of NASA-LeRC. Compared to the Rocketdyne data, the rotational effect $\Delta f_{\%}$ for NASA data is more important. This is due to the NASA tester having relatively lower pressure across the fluid film combined with the same order of rotational speed. Similar to Table 13, Table 15 demonstrates that without surface roughness effects included, the accuracy is very poor. With the surface roughness effects included, the error is again reduced to within 15%. The good agreement between data and prediction lead to several conclusions:

1. The quality of the data is good.

2. The surface roughness effect model is accurate and is able to predict the pressure drop or leakages for two independent sets of test data.

3. The predicted radial clearance is close to actual operation condition. (It must always be noted that operating radial clearance is an analytically derived value. Although sopnisticated finite element analysis is used, the a   cy is limited due to the lack of available input of the parameters e ecting clearance changes.)

TABLE 14. NASA HYBRID TESTER TEST DATA (JUNE BUILD, TURBINE SIDE)

(S.I. UNITS)

TEST/ SLICE NO.	CARTRIDGE SPEED, RAD/S	C, MM	$\dot{M}$, KG/S	ρ, KG/M3	μ, N/M-S	U_A, M/S	U_R, M/S	R_A	R_R	F	F_R	ΔF, %	F'
N303	0	0.0698	0.056	62	83.2×10^{-6}	46.9	0	4.8×10^{4}	0	0.0213	0.0213	0	0.051
N3408	4163	0.0632	0.039	61	80.3×10^{-6}	35.3	91.4	3.4×10^{4}	4.3×10^{4}	0.0233	0.0314	35	0.070
N3602	6088	0.0559	0.0508	62	83.2×10^{-6}	53.0	133.5	4.3×10^{4}	5.4×10^{4}	0.0219	0.0294	34.6	0.076
N3701	7192	0.0508	0.0608	112	93.4×10^{-6}	67.7	157.9	4.54×10^{4}	5.4×10^{4}	0.0216	0.0288	31.6	0.0765

(ENGLISH UNITS)

TEST/ SLICE NO.	RPM CARTRIDGE	C, INCH	$\dot{M}$, $\frac{LBM}{SEC}$	ρ, $\frac{LBM}{F^3}$	μ, $\frac{LBM}{F\text{-}SEC}$	U_A, FPS	U_R, FPS	R_A	R_R	F	F_R	ΔF, %	F'
N303	0	0.00275	0.124	3.87	5.7×10^{-6}	154	0	4.8×10^{4}	0	0.0213	0.0213	0	0.051
N3408	39,750	0.00249	0.085	3.8	5.5×10^{-6}	116	300	3.4×10^{4}	4.3×10^{4}	0.02327	0.0314	35	0.07
N3602	58,136	0.00220	0.112	3.87	5.7×10^{-6}	174	438	4.3×10^{4}	5.4×10^{4}	0.0219	0.0294	34.6	0.076
N3701	68,676	0.00200	0.134	4.0	6.4×10^{-6}	222	518	4.54×10^{4}	5.4×10^{4}	0.0216	0.0288	31.6	0.0765

TABLE 15. COMPARISON BETWEEN NASA MEASURED DATA AND PREDICTION

(S.I. UNITS)

TEST/ SLICE NO.	MEASURED $\Delta P, N/CM^2$	PREDICTED WITH F		PREDICTED WITH F_R		PREDICTED WITH F'	
		$\Delta P, N/CM^2$	% ERROR	$\Delta P, N/CM^2$	% ERROR	$\Delta P, N/CM^2$	% ERROR
N3003	31	21	33	21	33	36	14.7
N3408	23	11	53	11	52	27	14.7
N3602	72	30	58	36	50	73	0.9
N3701	134	54	60	64	52	134	0.5

(ENGLISH UNITS)

TEST/ SLICE NO.	MEASURED ΔP, PSI	PREDICTED WITH F		PREDICTED WITH F_R		PREDICTED WITH F'	
		ΔP, PSI	% ERROR	ΔP, PSI	% ERROR	ΔP, PSI	% ERROR
N3003	45	30.2	33	30.2	33	51.6	14.7
N3403	34	16	53	16.3	52	39	14.7
N3602	105	44	58	52.7	50	106	0.9
N3701	195	78	60	93	52	194	0.5

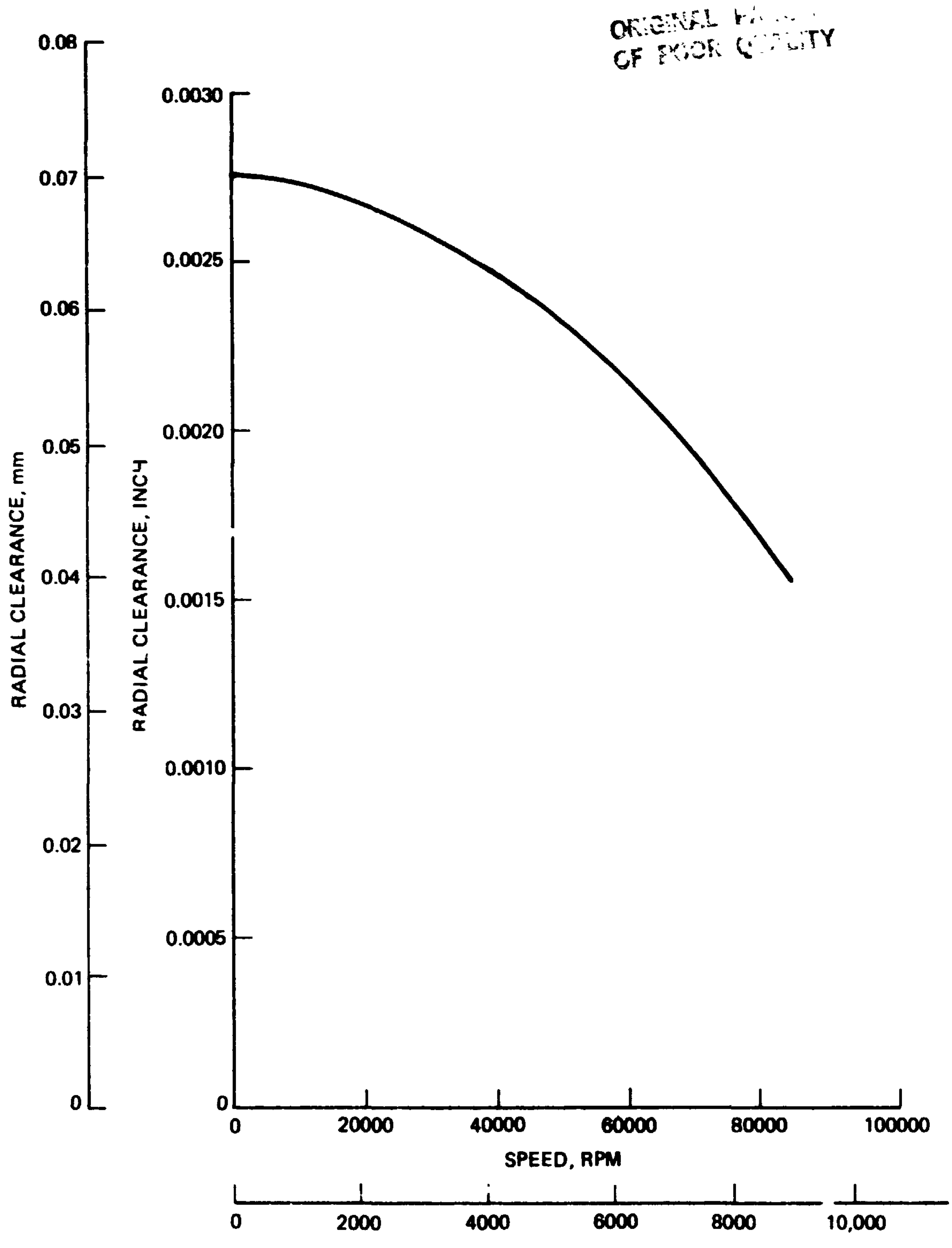

Figure 109. NASA Tester - June Build Radial Clearance

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Bearing Dynamic Coefficient Effect. Hydrostatic bearing forces exert a significant influence on the dynamic behavior of rotating machinery. The fluid in the bearing produces forces F_x and F_y on the journal which can be written as:

$$\begin{Bmatrix} F_x \\ F_y \end{Bmatrix} = - \begin{bmatrix} K_{xx} & K_{xy} \\ -K_{yx} & K_{yy} \end{bmatrix} \begin{Bmatrix} X \\ Y \end{Bmatrix} - \begin{bmatrix} C_{xx} & C_{xy} \\ -C_{yx} & C_{yy} \end{bmatrix} \begin{Bmatrix} \dot{X} \\ \dot{Y} \end{Bmatrix} \quad (15)$$

The direct stiffness K_{xx}, K_{yy} and direct damping C_{xx} and C_{yy} in the matrix act as stabilizers and the off-diagonal, cross-coupling terms are destabilizers. The cross-coupling terms are a function of the rotation-induced Couette flow. The direct stiffness and direct damping coefficients are generated from the pressure differences across the bearing and have a very weak dependency on the rotational speed. On the other hand, the cross-coupling terms are directly proportional to the rotational speed. If there is no rotation, Eq. 15 can be simplified to:

$$\begin{Bmatrix} F_x \\ F_y \end{Bmatrix} = - \begin{bmatrix} K_{xx} & 0 \\ 0 & K_{yy} \end{bmatrix} \begin{Bmatrix} X \\ Y \end{Bmatrix} - \begin{bmatrix} C_{xx} & 0 \\ 0 & C_{yy} \end{bmatrix} \begin{Bmatrix} \dot{X} \\ \dot{Y} \end{Bmatrix} \quad (16)$$

by removing the cross-coupling terms as shown in Eq. 16, the direct stiffness and damping become more effective in improving the rotor stability. To achieve this purpose, a grooved hydrostatic bearing has been proposed (Ref. 15). By properly designing the grooved angle, the cross-coupling dynamic coefficients can be partially, if not totally, removed.

Since no dynamic coefficients were measured for Mark 48 pump test, the effect of rotation on the bearing performance was based on the predicted dynamic coefficients. According to previous predictions (Ref. 13) as reproduced in Fig. 65, 66, 67 and 68, the cross-coupling dynamic coefficients are about 10 to 20% of the direct terms within the range of the operational speed. This implies that the bearing load capacity will reduce by 10 to 20% if the rotation effect is taken into account. A more detailed rotordynamic analysis can provide a clearer insight of the rotational effects on the system dynamic behavior.

Bearing Analysis Conclusions. The basic conclusions that can be drawn from analysis of the test data on the hybrid bearing are as follows:

1. Within the operational range of speed, the rotation effect on the mass flowrate test values is less than 20%. The analytical model shows no effect of speed on the flowrate for a constant clearance.

2. The test data flowrate values were approximately 30% lower than the predicted values using a smooth bearing surface assumption. The surface roughness effects are much greater than the rotation effects. Assuming the operating clearances are determinable and neglecting the effective surface roughness, the friction coefficient can be underestimated by a factor of 3.

3. The calculated pressure drop across the bearing based on the empirically derived friction coefficient with rotation and surface roughness effects included agrees fairly well with data. The difference between the developed prediction and measured data are within 15% over the wide range of speed.

4. The feasibility of incorporating hydrostatic/ball bearings in a high-speed turbopump for cryogenic applications has been demonstrated. The achieved cartridge liftoff of the pump-end bearing and operation at shaft speed has verified the theory of hybrid bearing operation.

5. The observed speed difference between the cartridge and shaft at high steady-state speeds was due to the effect of the cartridge rubbing rather than torque differences between the hydrostatic and ball bearing. The viscosity effect due to temperature change on this speed difference is negligible. The light touching of the cartridge was caused by the high vibration amplitudes at the high speeds.

6. Several trends of data observed in the testing agree well with theory. These are: the flowrate increases with pressure differential across the bearing, the pressure ratio increases with cartridge speed and decreases with clearance, and the fluid film resistance calculated from test data decreases with increasing clearance.

7. Most data follow the trends predicted except for a few scattered points, which are data points No. 1, 2, 16, 17, 18, and 19. These are associated with relatively low shaft speed and internal flow. The actual cause for the scattering has not been determined. Test points 16, 18, and 19 are data where choking at the fluid film exit may be occurring.

8. Test data indicated a decreasing trend of the flowrate with increasing bearing number, Λ, even when the latter is small. Theory, however, shows no significant effect if Λ has a low value (0 to 0.1), which means the Couette effect at low rotational effect is negligible in a dominantly hydrostatic bearing. The cause of the deviation from theoretical prediction has not been determined.

9. The data indicate high vibrations and subsynchronous whirl during Test No. 14 were not caused primarily by bearing damping breakdown, as the squeeze number was quite low when these occurred. Data show that some other data points which operated with stability did have higher squeeze numbers. In this type of turbopump where there is a large shaft span between the bearings, it may be beneficial to provide other shaft damping independent of the hybrid bearing. An example of this

would be fluid film damping in the place of labyrinth seals. This would have increased the stability considerably. The bearing rubbing at other times is a consequence of excessive shaft bow at the bearing.

Dynamic Analysis and Performance

The analysis of the dynamic data for the Mark 48-F turbopump testing with hybrid bearing was completed. Two critical speeds were detected that correspond to the second and third analytical critical speeds. The test data verify that a wide spectrum of control of rotordynamic parameters can be maintained by the hydrostatic bearing supply pressure level available to the turbopump. The analysis also indicates that the accuracy of the predictions of rotordynamic behavior hinges on the accuracy of the predictions of direct and cross-coupled stiffness and damping values. Empirical verification of these values is basic to the evaluation of the hydrostatic bearing potential and the probability of wide range rotordynamic control by hydrostatic bearing parameters. The analysis for this study of turbopump rotordynamics was made using the present state-of-the-art capability for prediction of these parameters.

The rotordynamic analysis of the turbopump test data was developed in detail. The analysis consisted of seven different areas of study as follows:

A - Individual Test Summaries

B - Critical Speed Analysis

C - Subsynchronous Whirl

D - Synchronous Harmonics of Shaft Speed

E - General Bearing-Cartridge Performance

F - Rotordynamic Analysis Conclusions

G - Recommendations

Each area of analysis is presented in detail below.

Individual Test Summaries. A test-by-test summary is presented in Table 16 for the 15 Mark 48F turbopump tests using hybrid bearings. Included in the information listed for each test are maximum pump and bearing cartridge speeds, critical speeds and synchronous harmonics, maximum vibration levels, and any other dynamic phenomena detected during testing. The most notable of these events is the subsynchronous vibration which was seen at approximately 50% of shaft speed during the high-speed portions of tests 012 and 014. Also of interest are the

TABLE 16. ROTORDYNAMIC TEST DATA

SUMMARY - HYBRID BEARINGS

TEST NO.	SPEED START SPEED STOP, IRIG TIME	MAXIMUM SHAFT SPEED, RAD/S (RPM)	MAXIMUM PUMP CARTRIDGE SPEED, RAD/S (RPM)	MAXIMUM TURBINE CARTRIDGE SPEED, RAD/S (RPM)	CRITICAL SPEEDS, RAD/S (RPM)	MAXIMUM VIBRATION LEVEL: G RMS	SYNCHRONOUS HARMONICS	COMMENTS AND OBSERVATIONS
1	16:55:52 16:58:54	138 (1320)	138 (1320)	0 (0)	NONE	NOT MEASURABLE	NONE	WINDMILLING
2	17:40:06 17:44:45	199 (1900)	199 (1900)	0 (0)	NONE	NOT MEASUREABLE	NONE	WINDMILLING
3	10:49:04 10:49:15	2827 (27,000)	859 (8200)	86.4 (825)	NONE	NOT AVAILABLE	NOT AVAILABLE	PREMATURE CUT DUE TO OVER-SPEED. NO DATA REDUCTION PERFORMED.
4	11:39:51 11:43:46	2513 (24,000)	2513 (24,000)	262 (2500)	NONE	4.7 PUMP RADIAL ACCELEROMETER	NONE	TURBINE CARTRIDGE SPUN DURING STARTUP ONLY. CASING RESO-NANCE AT 970 HZ.
5	15:13:10 15:13:23	3204 (30,600)	1047 (10,000)	52.4 (500)	NONE	NOT AVAILABLE	NOT AVAILABLE	PREMATURE CUT AT STARTUP. NO DATA REDUCTION PERFORMED.
6	15:47:50 15:49:00	3508 (33,500)	3508 (33,500)	10.5 (100)	NONE	5.6 PUMP RADIAL ACCELEROMETER	NONE	TURBINE CARTRIDGE ROTATES SLOWLY (2.6 TO 3.1 RAD/S; 25 TO 30 RPM) DURING MOST OF TEST. 3/2 HARMONIC SEEN ON TURBINE AXIAL ACCELEROMETER.
7	16:39:54 16:40:33	3487 (33,300)	3487 (33,300)	3.14 (30)	NONE	5.0 PUMP RADIAL ACCELEROMETER	NONE	TURBINE CARTRIDGE ROTATES SLOWLY (0 TO 3.14 RAD/S; 0 TO 30 RPM) DURING MOST OF TEST. 3/2 HARMONIC SEEN ON TURBINE AXIAL ACCELEROMETER.
8	15:23:43 15:26:47	6786 (64,800)	6786 (64,800)	70.7 (675)	3665 (35,000)	13.7 PUMP RADIAL ACCELEROMETER	FAINT 2X,3X PUMP RADIAL ACCEL-EROMETER	TURBINE CARTRIDGE ROTATES ONLY DURING STARTUP. CASING RESONANCE AT 970 HZ.

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TABLE 16. (CONTINUED)

TEST NO.	SPEED START SPEED STOP, IRIG TIME	MAXIMUM SHAFT SPEED, RAD/S (RPM)	MAXIMUM PUMP CARTRIDGE SPEED, RAD/S (RPM)	MAXIMUM TURBINE CARTRIDGE SPEED, RAD/S (RPM)	CRITICAL SPEEDS, RAD/S (RPM)	MAXIMUM VIBRATION LEVEL: G RMS	SYNCHRONOUS HARMONICS	COMMENTS AND OBSERVATIONS
9	13:50:28 13:52:23	136 (1300)	136 (1300)	0 (0)	NONE	NOT MEASURABLE	NONE	WINDMILLING
10	16:41:58 16:43:43	8514 (81,300)	7854 (75,000)	31.4 (300)	3707 (35,400) 8378 (80,000)	15.0 PUMP RADIAL ACCELEROMETER	2X,3X PUMP RADIAL ACCEL-EROMETER	TURBINE CARTRIDGE ROTATES ONLY DURING STARTUP. PUMP CARTRIDGE CAN'T OPERATE ABOVE 2854 RAD/S (75,000 RPM). CASING RESONANCE AT 950 TO 970 HZ.
11	15:51:40 15:57:57	5890 (56,250)	5890 (56,250)	513 (4900)	3581 (34,200)	15.0 PUMP RADIAL ACCELEROMETER	NONE	TURBINE PRESSURE RATIO WAS INCREASED FOR THIS TEST. TURBINE CARTRIDGE SPUN SLOWLY (0 TO 16 RAD/S; 0 TO 150 RPM) WHEN SHAFT SPEED WAS BETWEEN 1885 AND 4189 RAD/S (18,000 AND 40,000 RPM). CASING RESONANCE AT 940 HZ.
12	13:07:37 13:10:55	9320 (89,000)	9163 (87,500)	3665 (35,000)	6283 (60,000)	18.5 TURBINE FLANGE RADIAL ACCELEROMETER	2X,3X PUMP RADIAL ACCEL-EROMETER	SUBSYNCHRONOUS WHIRL (700 HZ) ABOVE 7590 RAD/S (72,000 RPM) SHAFT SPEED. TURBINE CARTRIDGE STARTED TO SPIN WHEN SHAFT SPEED EXCEEDED 8011 RAD/S (76,500 RPM). HIGH G LEVELS SEEN DURING DECEL WHEN SHAFT SEIZED AT 2200 RAD/S (21,000 RPM). CASING RESONANCE AT 570 HZ. TURBINE PRESSURE RATIO WAS FURTHER INCREASED FOR THIS TEST.

TABLE 16. (CONCLUDED)

TEST NO.	SPEED START SPEED STOP, IRIG TIME	MAXIMUM SHAFT SPEED, RAD/S (RPM)	MAXIMUM PUMP CARTRIDGE SPEED, RAD/S (RPM)	MAXIMUM TURBINE CARTRIDGE SPEED, RAD/S (RPM)	CRITICAL SPEEDS, RAD/S (RPM)	MAXIMUM VIBRATION LEVEL: G RMS	SYNCHRONOUS HARMONICS	COMMENTS AND OBSERVATIONS
13	13:34:54 13:35:01							NO FM TAPE WAS RECORDED FOR TEST 13. TEST CUTOFF AT START
14	13:40:54 13:43:26	9111 (87,000)	6859 (65,500)	2618 (25,000)	7645 (73,000)	20 PUMP RADIAL ACCELEROMETER	2X,3X,4X, PUMP RADIAL ACCEL-EROMETER	SUBSYNCHRONOUS WHIRL (700 HZ) ABOVE 78,500 RPM SHAFT SPEED. TURBINE CARTRIDGE SPINS SLOWLY ABOVE 8482 RAD/S (81,000 RPM) SHAFT SPEED. PUMP AND TURBINE CARTRIDGES BOTTOM OUT AGAINST BEARING SURFACE AT HIGH SPEED. CASING RESONANCE AT 960 HZ.
15	14:17:47 14:17:48	12.6 (120)	12.6 (120)	12.6 (120)	NONE	8.5 PUMP RADIAL ACCELEROMETER	NONE	PUMP FAILED TO TURN. SHAFT MAY HAVE JACK-HAMMERED AS INDICATED BY AXIAL PROXIMITY PROBE WHICH SAW REPEATED BACK AND FORTH SHAFT MOTION.

970 Hz resonance, which appears to have been a casing mode, and the unusual 3/2 harmonic seen during tests 006 and 007.

Critical Speeds. Two critical speeds were identified during testing, one at 3665 radians/sec (35,000 rpm) and another at speeds varying from 5760 to 8378 radians/sec (55,000 to 80,000 rpm), depending on the magnitude of the hydrostatic bearing supply pressures used and the operation of the turbine bearing cartridge. They will be referred to as the first and second critical speed in this discussion.

1. First Critical Speed

   The first critical speed was detected at approximately 3665 radians/sec (35,000 rpm) for tests 008, 010, and 011. Shaft deflection plots from radial proximity probes (Bentlys) and acceleration plots from the pump-end radial accelerometers (PRA) are given in Fig. 110 to 113 and 114 to 117, respectively. They show the critical speed's presence during tests 010 and 011 (Fig. 110, 111, 114, and 115). The radial Bentlys also indicated a phase change, an example of which is shown in Fig. 118 for test 011. High bearing supply pressures were used during these three tests (pressures higher than the turbopump is capable of providing). This condition was analyzed in initial studies, but those pressures combined with the turbine cartridge's inability to turn due to axial loading (see the section on turbine cartridge performance) produced pump-end and turbine-end springrate, which had not been previously analyzed. This makes a comparison of this critical speed to any analytical data impossible without further in-depth analysis.

   During tests 012 and 014, the first critical speed was not seen on accelerometer data, but are evident on Bently data (Fig. 112 and 113). These tests used pump-fed bearing pressures (pressures the turbopump provided). The turbine cartridge at startup was rotating at about 838 radians/sec (8000 rpm) when the shaft was at 3665 radians/sec (35,000 rpm). This mode probably corresponds to the second analytically predicted critical speed shown in Fig. 119. Correlation of subsynchronous whirl frequencies with the second predicted mode adds more confidence to this assumption (see sections on subsynchronous whirl). Table 17 shows the pressure drops across each bearing for tests 010, 011, 012, and 014 at 3665 radians/sec (35,000 rpm).

2. Second Critical Speed

   The second critical speed was detected during tests 010, 012, and 014 (all the high-speed tests). Pump radial accelerometer and radial shaft deflection plots for test 010 (Fig 110 and 114) indicate that the critical did not appear until almost 8378 radians/sec (80,000 rpm). The phase change for test 010 (top of Fig. 120) also shows this. Like the first detected critical for test 010, this critical cannot be compared to any analytical results because of the lack of turbine cartridge rotation due to axial loading.

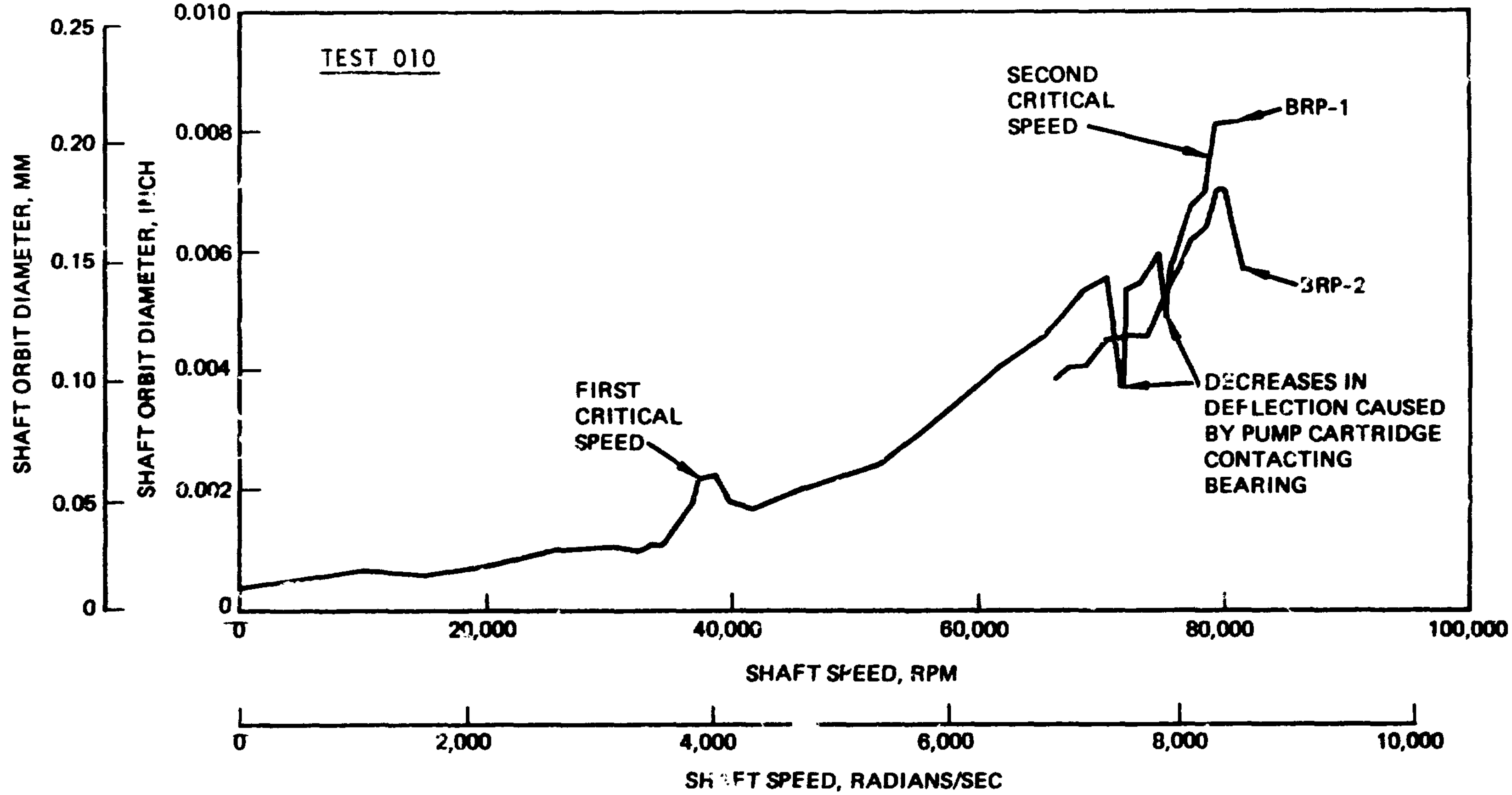

Figure 110. Shaft Orbit Characteristic From Radial Proximeters - Test 010

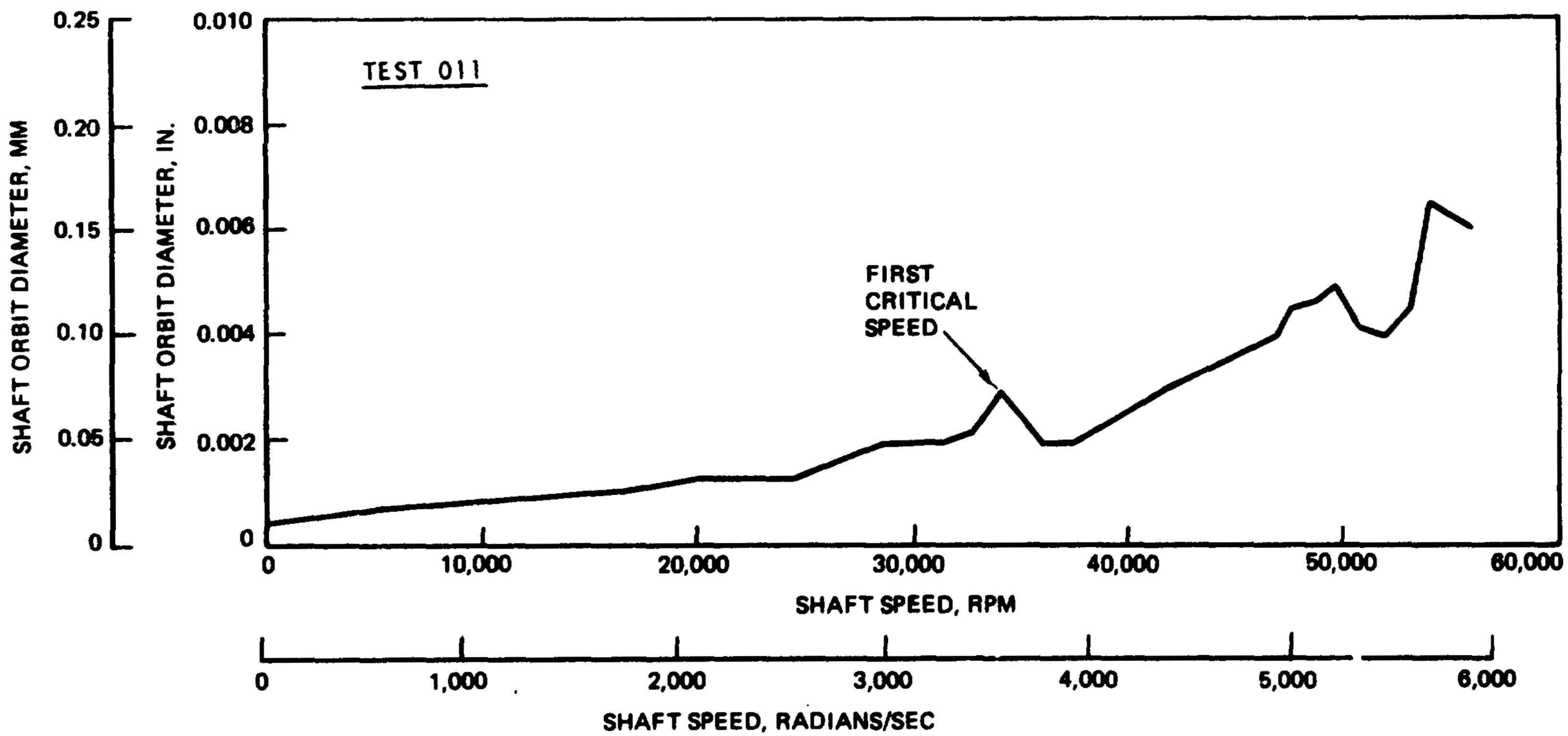

Figure 111. Shaft Orbit Characteristic From Radial Proximeters - Test 011

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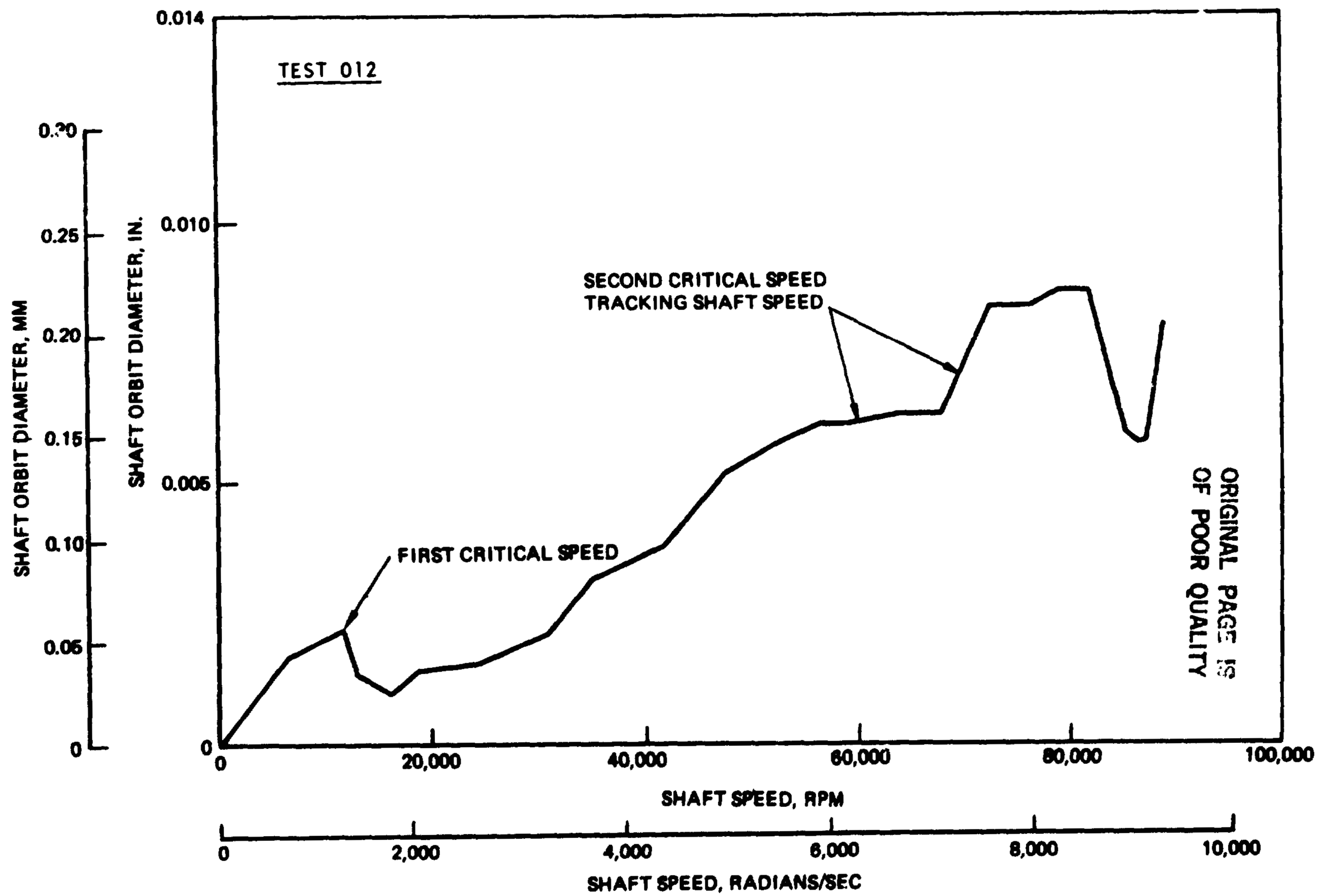

Figure 112. Shaft Orbit Characteristic From Radial Proximeters - Test 012

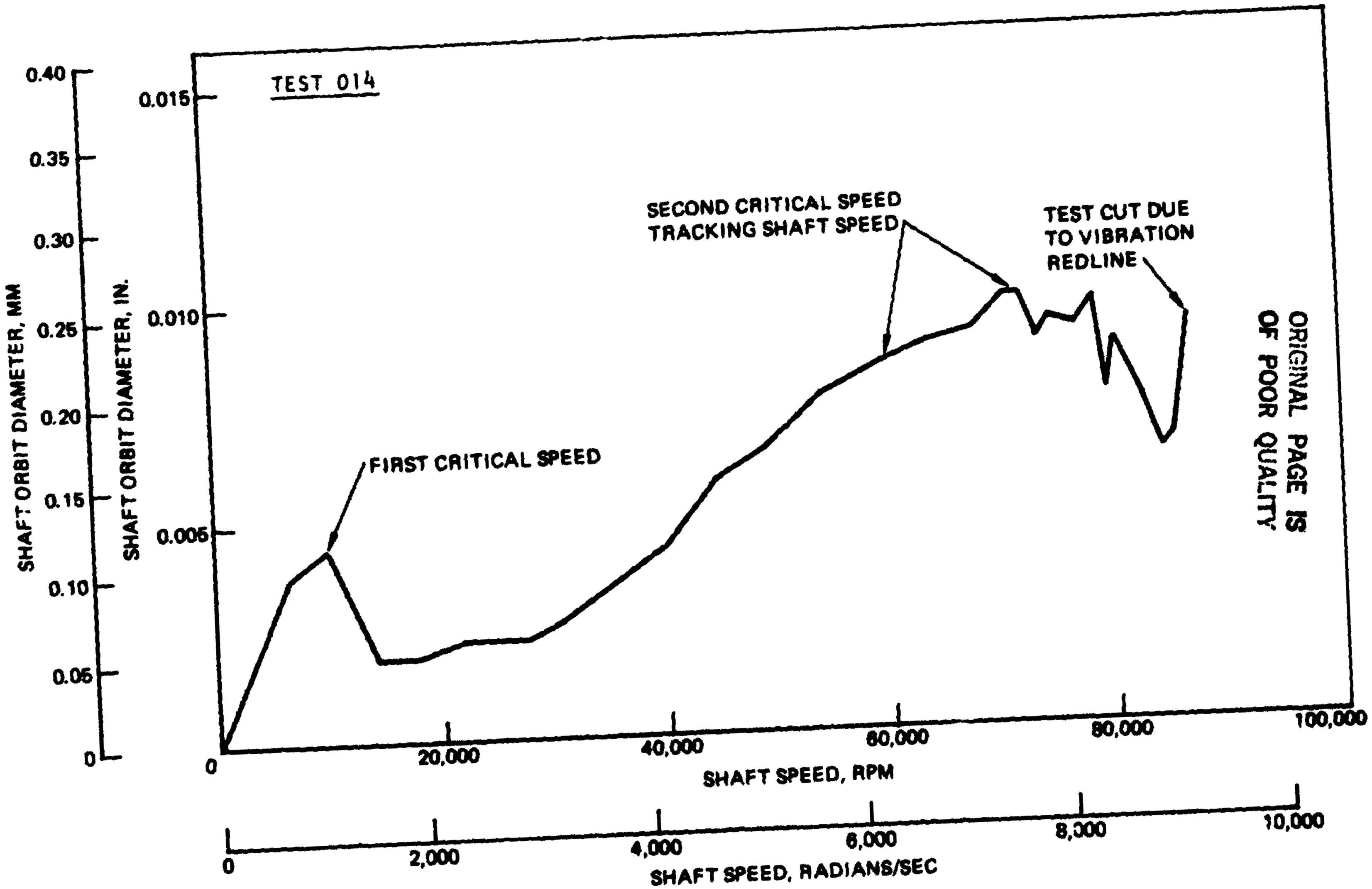

Figure 113. Shaft Orbit Characteristic From Radial Proximeters - Test 014

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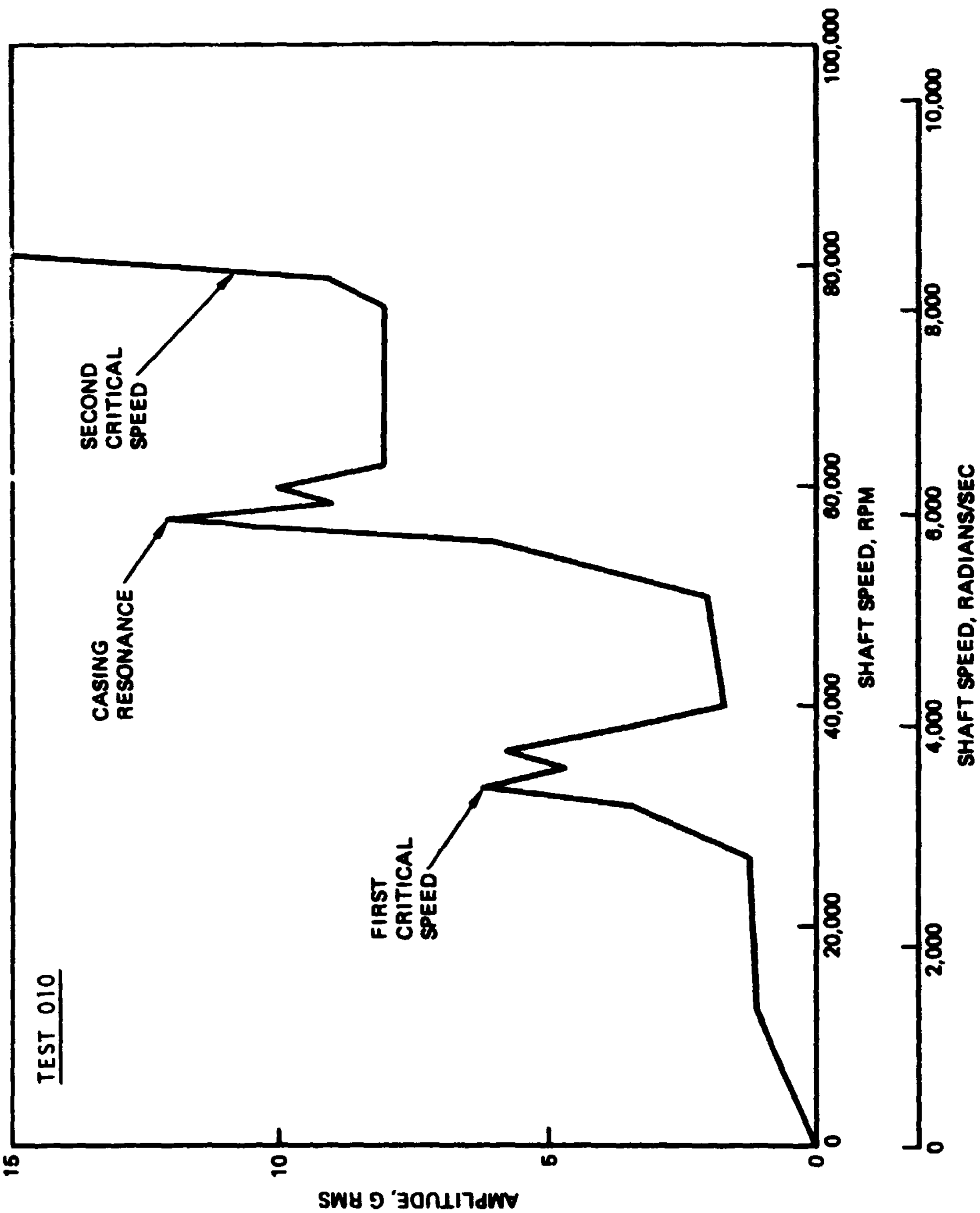

Figure 114. Pump-End Radial Accelerometer Response - Test 010

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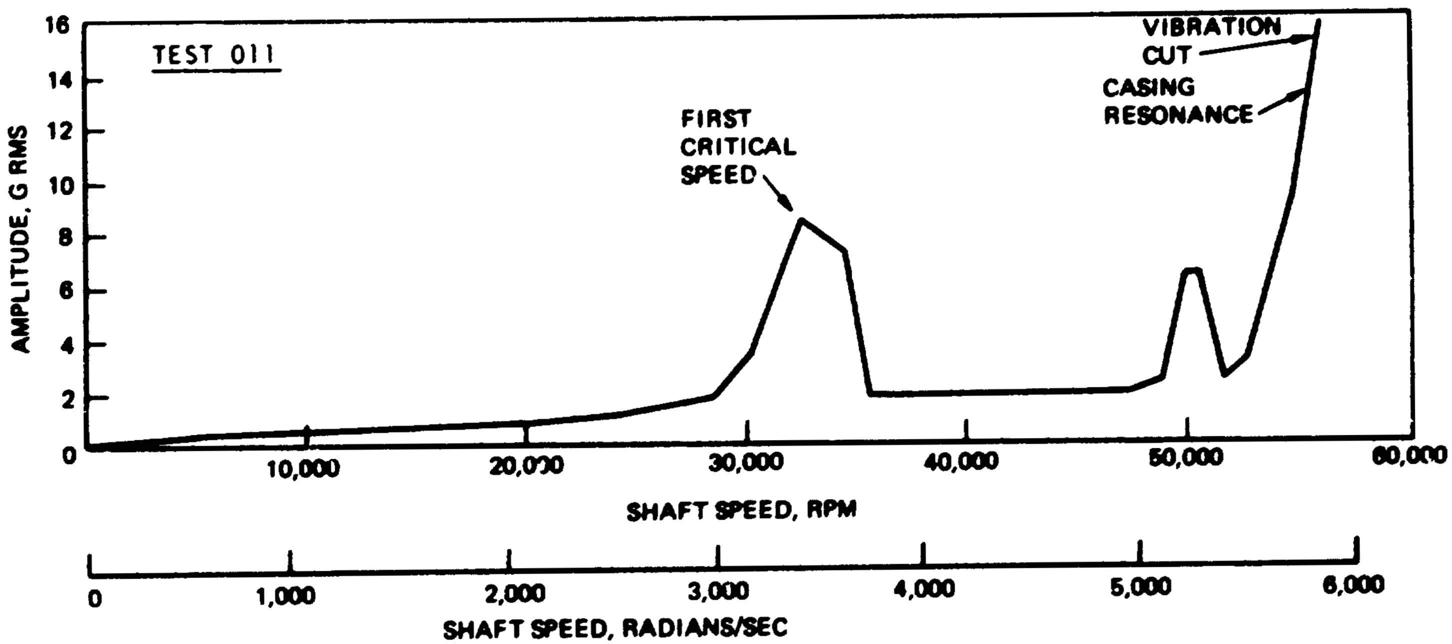

Figure 115. Pump-End Radial Accelerometer Response - Test 011

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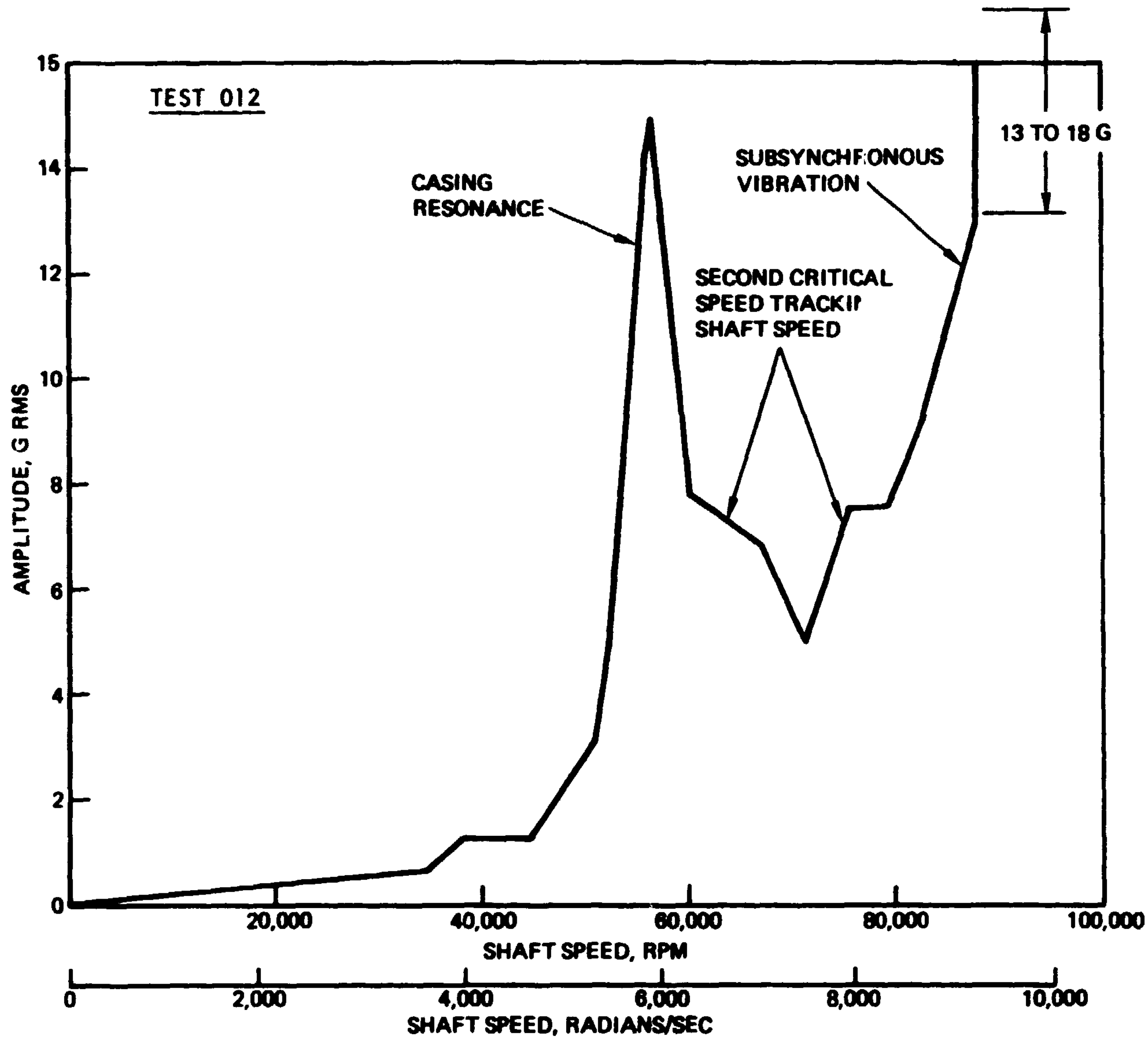


Figure 116. Pump-End Radial Accelerometer Response - Test 012

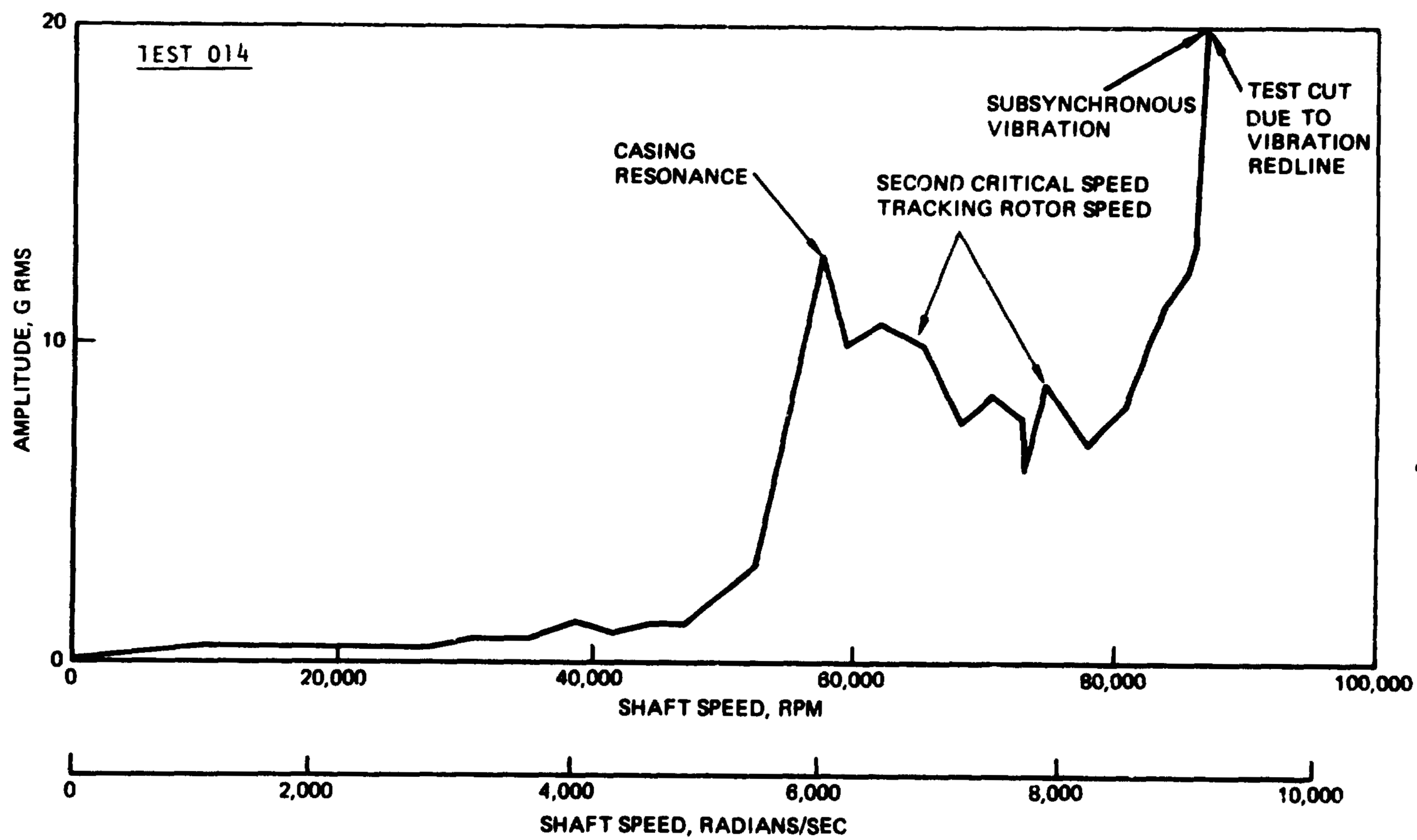
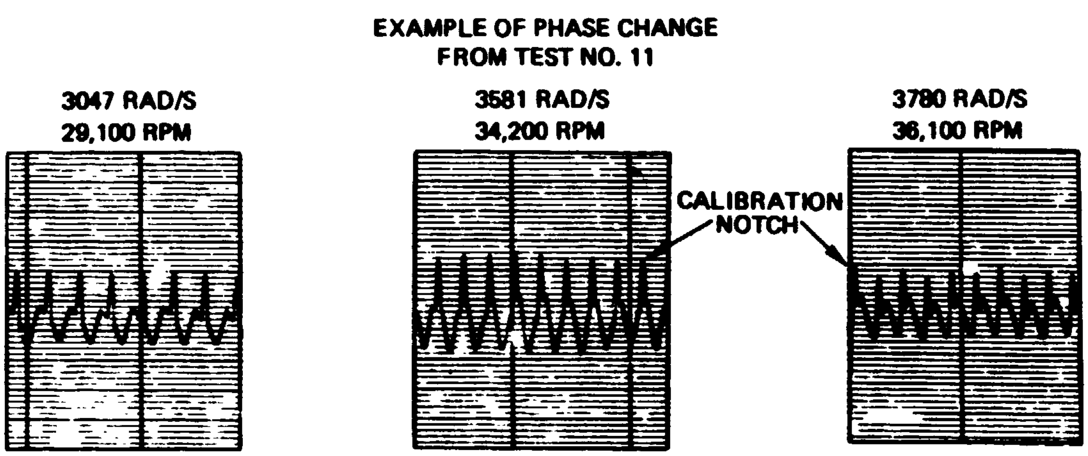


Figure 117. Pump-End Radial Accelerometer Response - Test 014

TEST NO.	SHAFT SPEED, RPM	SHAFT SPEED, RADIANS/SEC
08	35,000	3665
10	35,400	3707
11	34,200	3581



PHASE CHANGE IS SHOWN BY BENTLY RADIAL PROXIMETER
BRP-1 FOLLOWING A 0.066 MM (0.0026 INCH)
GLITCH CUT INTO SHAFT

Figure 118. First Critical Speed Evidence of Phase Change - Test 011

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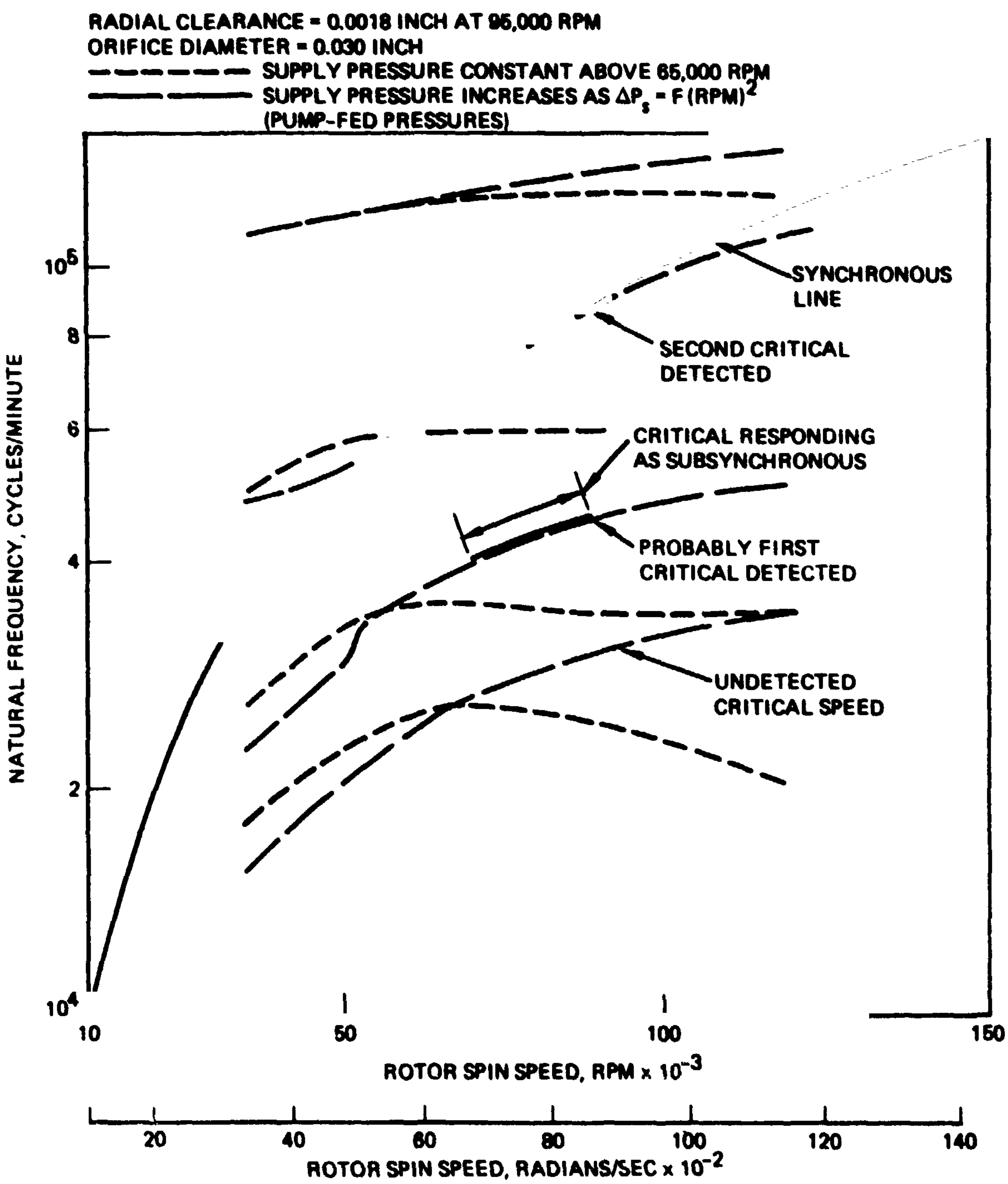

Figure 119. Turbopump Rotordynamic Critical Speed With Subsynchronous Response

TABLE 17. HYBRID BEARING TESTS - PRESSURE DROP ACROSS HYDROSTATIC BEARINGS

SHAFT SPEED, RAD/S	TEST 10 PUMP BEARING $\Delta P, N/CM^2$	TEST 10 TURBINE BEARING $\Delta P, N/CM^2$	TEST 11 PUMP BEARING $\Delta P, N/CM^2$	TEST 11 TURBINE BEARING $\Delta P, N/CM^2$	TEST 12 PUMP BEARING $\Delta P, N/CM^2$	TEST 12 TURBINE BEARING $\Delta P, N/CM^2$	TEST 14 PUMP BEARING $\Delta P, N/CM^2$	TEST 14 TURBINE BEARING $\Delta P, N/CM^2$
(S.I. UNITS)								
3665	290	262	172	252	83	152	79	162
5236	693	1172			169	300	148	262
5760	696	1258			207	390	207	372
6283	703	1251			234	452	272	483
6806	703	1210			283	524	307	552
7330	703	1093			324	600	355	627
7854	710	993			393	724	430	734
8378	696	855			465	841	459	834

SHAFT SPEED, RPM	TEST 10 PUMP BEARING ΔP, PSI	TEST 10 TURBINE BEARING ΔP, PSI	TEST 11 PUMP BEARING ΔP, PSI	TEST 11 TURBINE BEARING ΔP, PSI	TEST 12 PUMP BEARING ΔP, PSI	TEST 12 TURBINE BEARING ΔP, PSI	TEST 14 PUMP BEARING ΔP, PSI	TEST 14 TURBINE BEARING ΔP, PSI
(ENGLISH UNITS)								
35,000	420	380	250	365	120	220	115	235
50,000	1005	1700			245	435	215	380
55,000	1010	1825			300	565	300	540
60,000	1020	1815			340	655	395	700
65,000	1020	1755			410	760	445	800
70,000	1020	1585			470	870	515	910
75,000	1030	1440			570	1050	624	1065
80,000	1010	1240			675	1220	665	1210

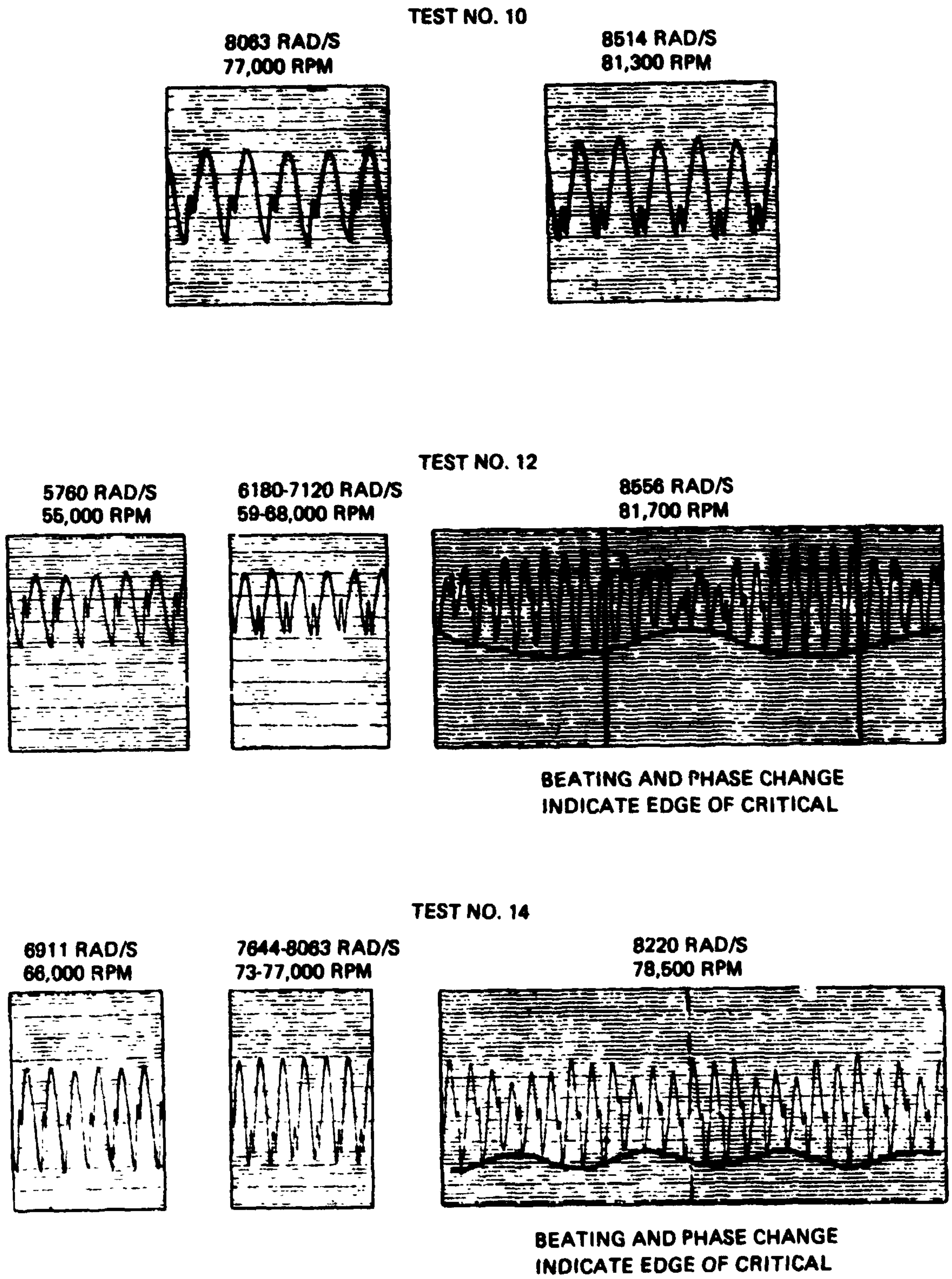

Figure 120. Second Critical Speed - Evidence of Phase Change - Tests 010, 012, and 014 Bently Radial Proximeter

When pump-fed pressures of lower values were used during tests 012 and 014, the critical speed appeared at a much lower speed and seemed to track rotor speed. This is shown by pump radial accelerometer and radial shaft deflection plots (Fig. 112, 113, 116 and 117) and also by phase changes illustrated by Fig. 120. Test 012 shows the critical speed tracking from 5760 to 8587 rad/s (55,000 to 82,000 rpm), and test 014 shows tracking from 6912 to 8273 rad/s (66,000 to 79,000 rpm). This corresponds well with the third analytical critical which is shown to track rotor speed in Fig. 119. It must be noted that the turbine cartridge was loaded axially and did not rotate during almost all operation in the 5236 to 8376 rad/s (50,000 to 80,000 rpm) range. This condition once again gives us an unknown turbine-end springrate. Table 1/ gives the pressure drops across each bearing for the critical's speed range.

3. Undetected Critical Speed

The first analytically predicted critical speed shown in Fig. 119 was never detected during any test. This mode was probably damped out due to the smaller amount of energy in the rotor at low speed and the extra damping provided by the hydrostatic bearings. It is unlikely that detection of the mode was missed due to inadequate instrumentation positioning. The very rapid accelerations of the shaft at startup to over 30,000 rpm also made detection difficult.

4. Casing Resonance

What appears to be a very sharp casing resonance was excited between 950 and 970 Hz on every test that passed through its frequency range. It can be seen on all pump-end radial accelerometer plots (Fig. 114, 115, 116, and 117) but does not show on any radial shaft deflection plots (Fig. 110, 111, 112, and 113). Figure 121 shows both the analytical and experimentally verified (rap test) mode that corresponds to this frequency level (Ref. 3).

This resonance was also detected during test 004 when shaft speed was only 2513 rad/s (24,000 rpm). The casing mode appeared as a supersynchronous vibration at 970 Hz. This unusual behavior is shown by the isoplot in Fig. 122.

Subsynchronous Whirl. Subsynchronous, synchronous, and supersynchronous data are detected on the isoplots of the pump radial accelerometer test data in Fig. 123 to 127. Rotative speed characteristics for the ends of tests 010, 012, and 014 are shown in Fig. 128 to 130. Subsynchronous whirl was encountered during two of the three tests which reached 8376 rad/s (80,000 rpm). It first appeared during test 012 when pump speed reached 8168 rad/s (78,000 rpm) as shown by Fig. 129 and continued until speed dropped to 7645 rad/s (73,000 rpm). It varied from 615 to 715 Hz (36,900 to 42,900 cycles per minute) and from 47% to 53.5% of pump speed. Figure 125 shows the subsynchronous whirl in isoplot form as well as synchronous vibration and several harmonics. Test 014 developed subsynchronous vibration when pump speed reached 8241 rad/s (78,700 rpm) as shown by Fig. 130 and continued until speed dropped to 8084 rad/s (77,200 rpm). It varied from 625 to 772 Hz

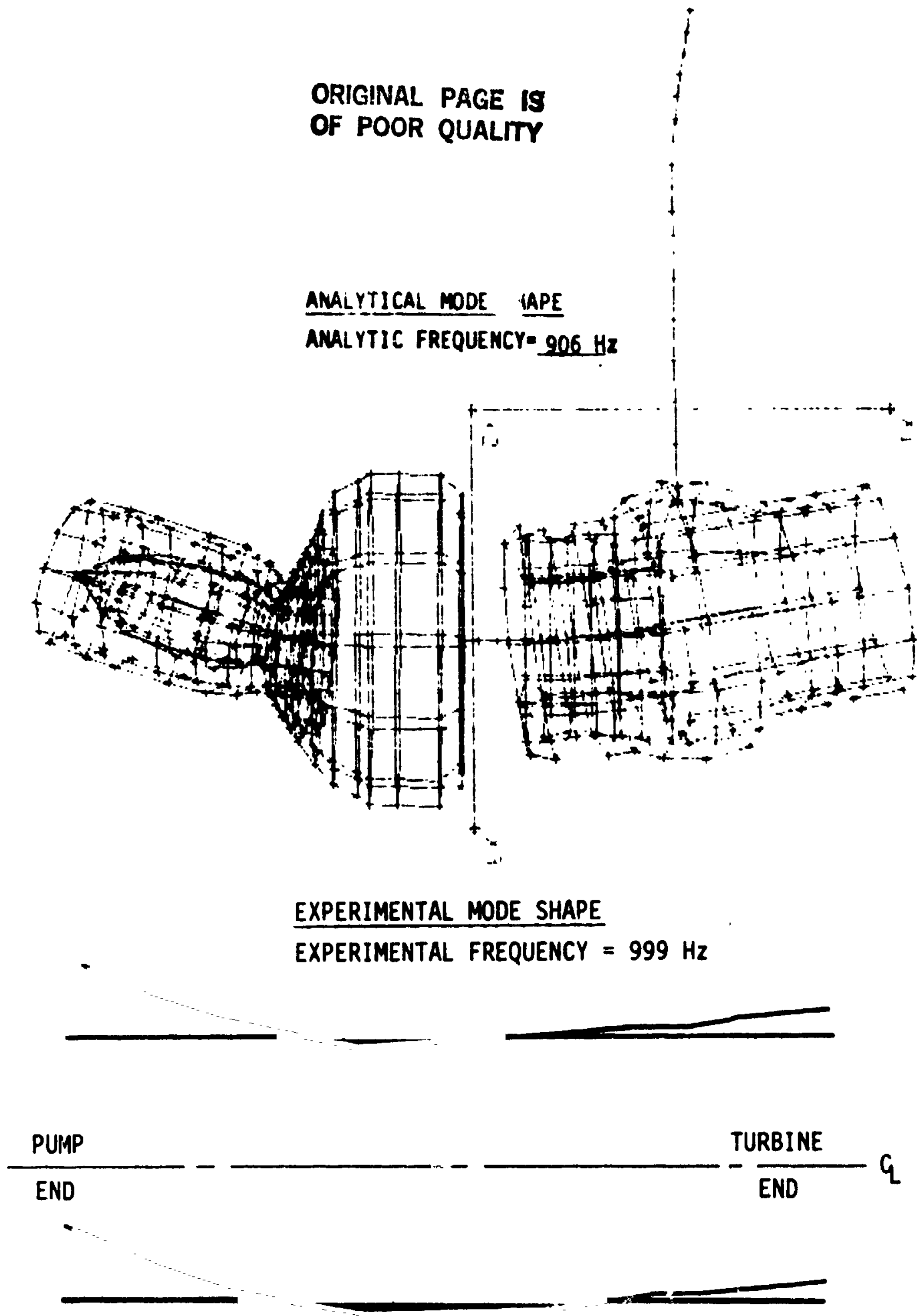

Figure 121. Test to Analysis Mode Shape Comparison of Turbopump Casing

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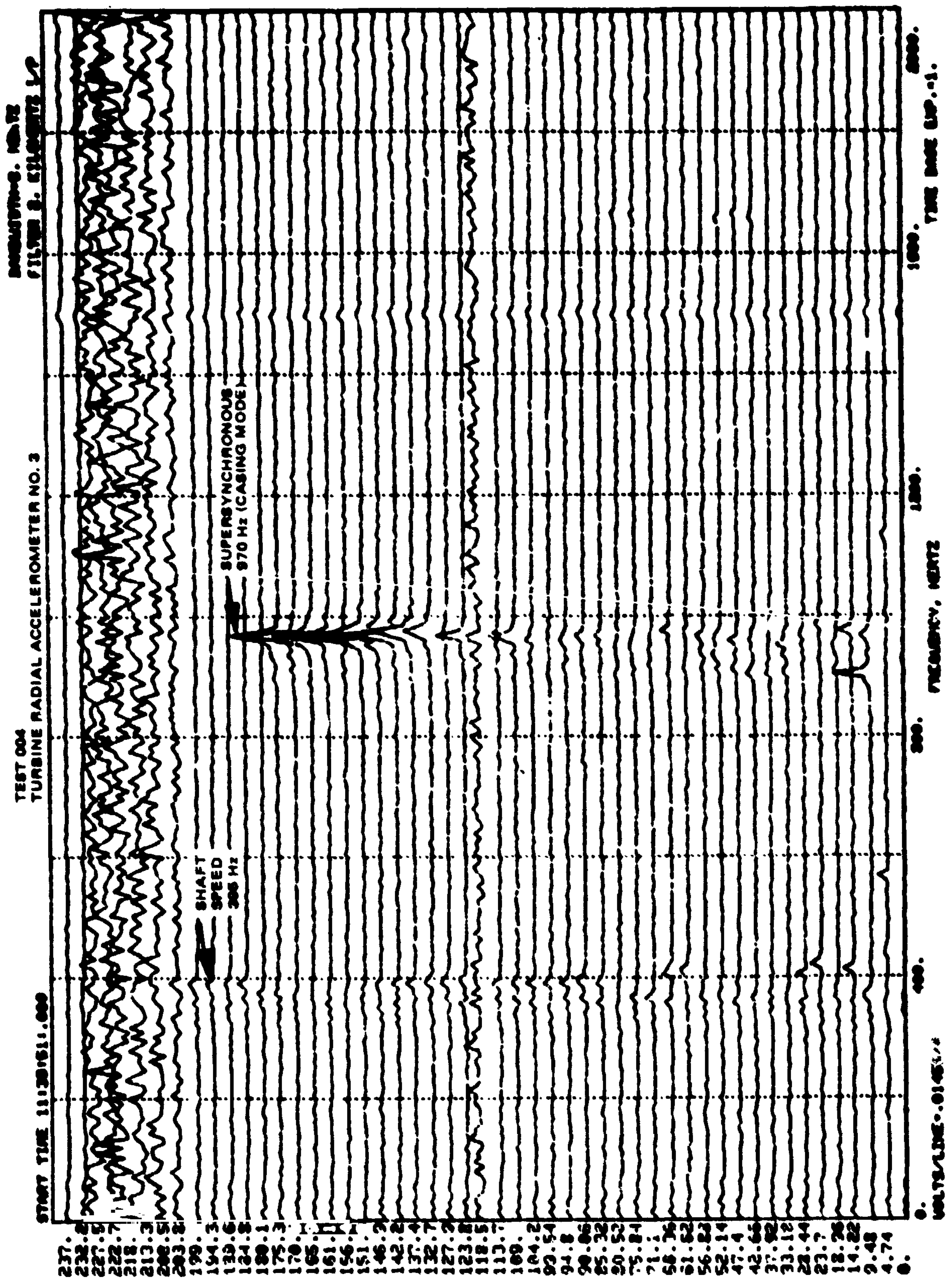

Figure 122. 970 Hz Casing Resonance Behaving As Supersynchronous Vibration - Test 004

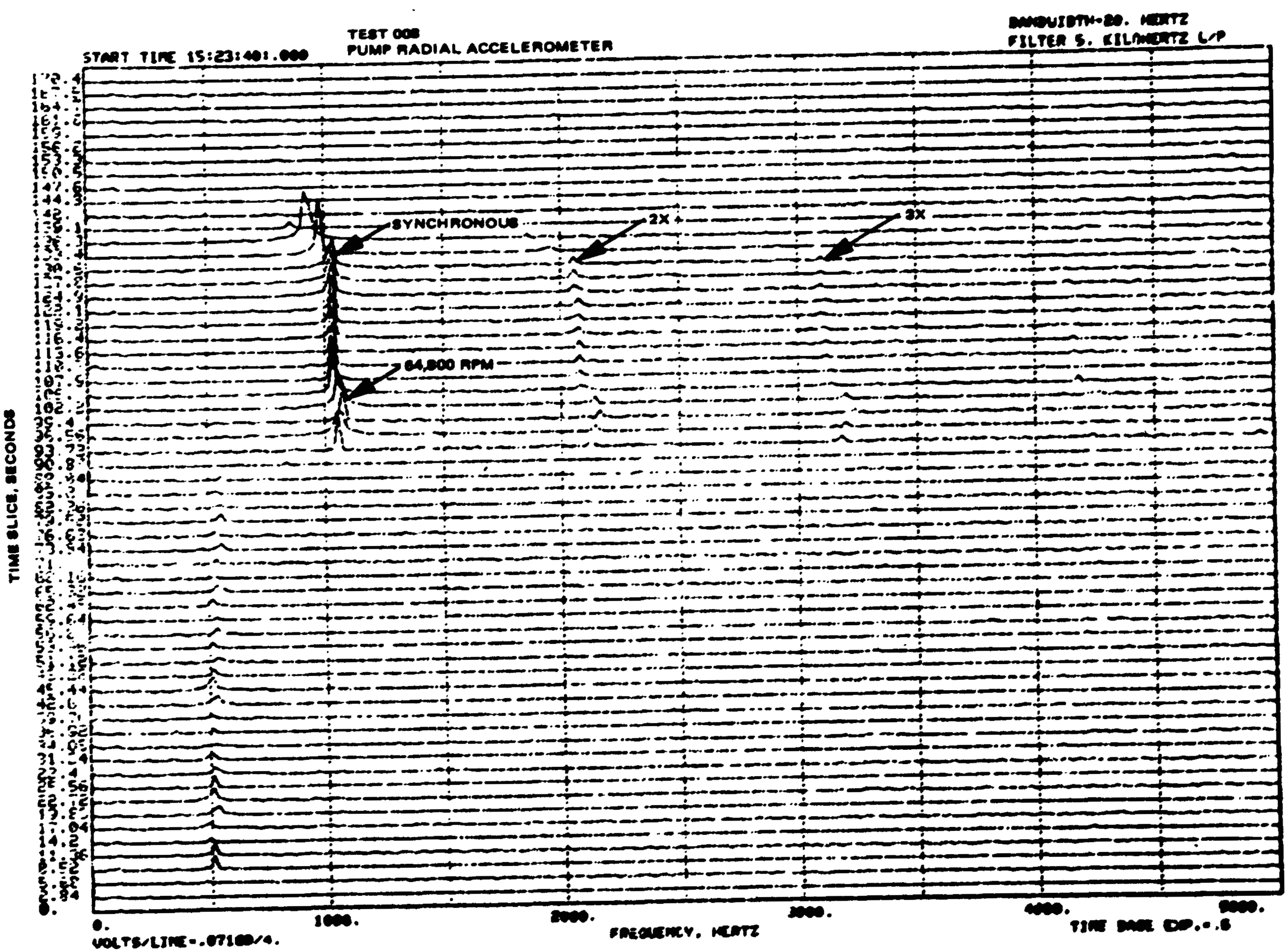

Figure 123. Synchronous Harmonics Indicating Rubbing - Test 008

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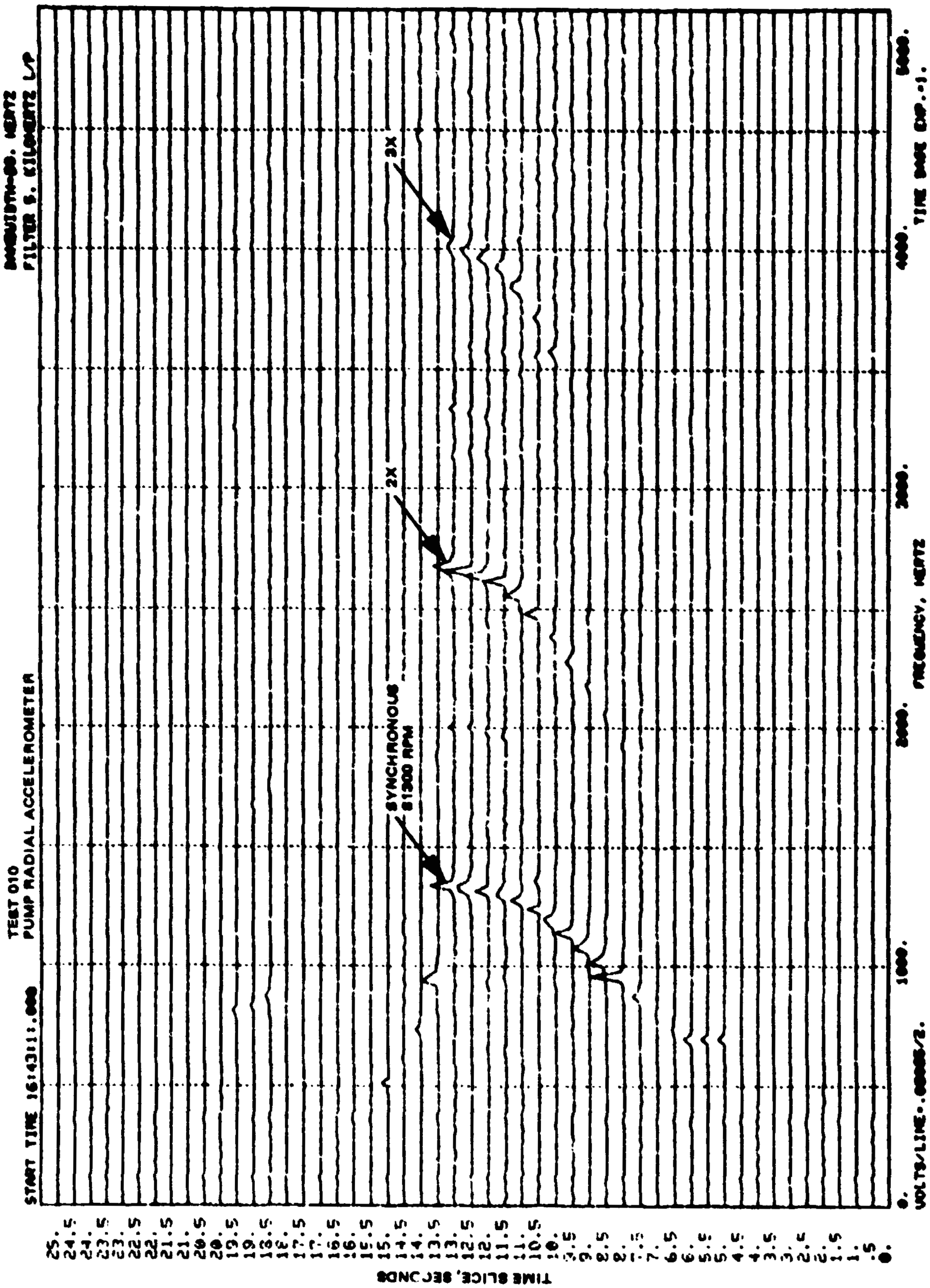

Figure 124. Synchronous Harmonics Indicating Rubbing - Test 010

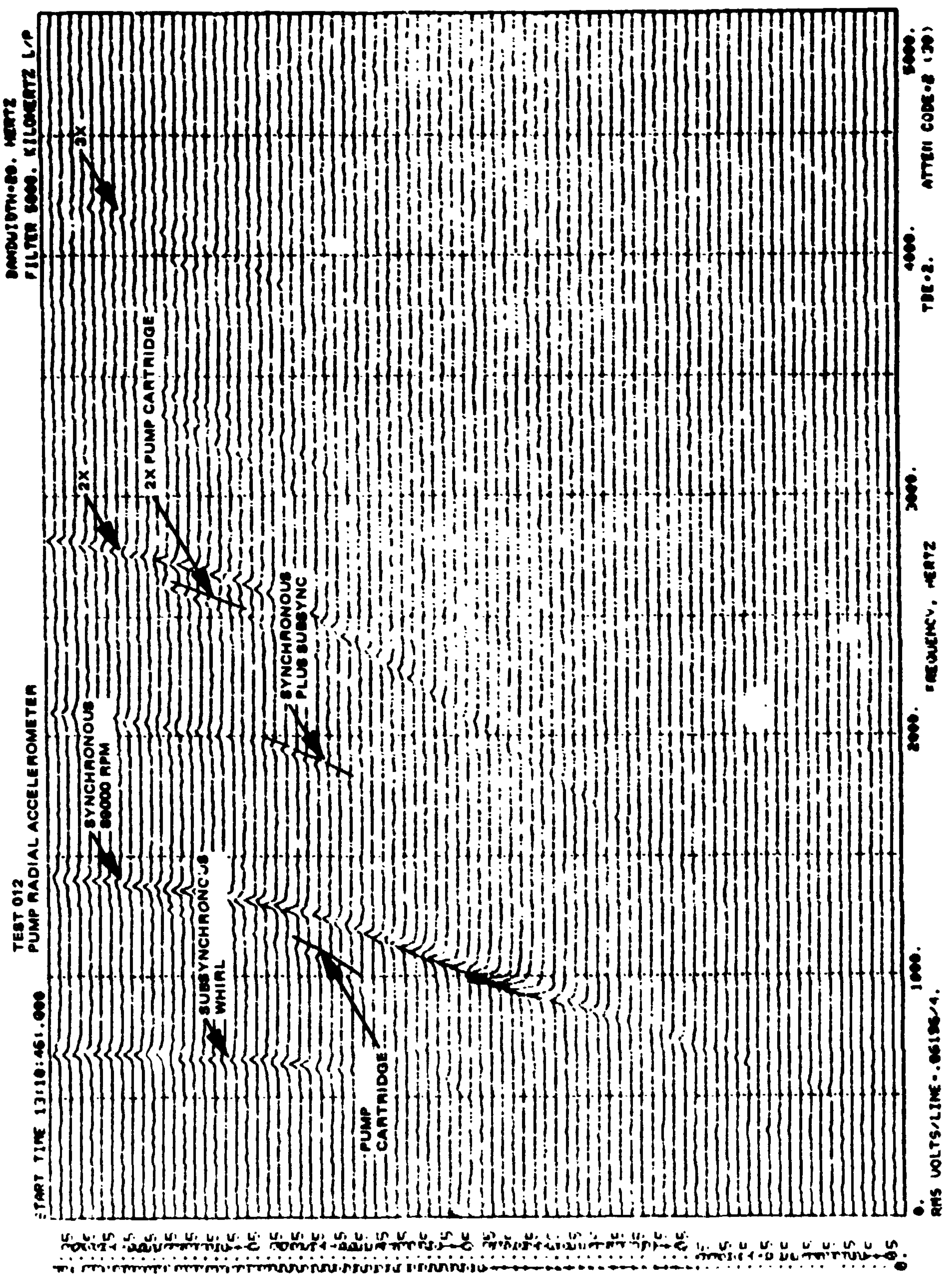

Figure 125. High-Speed Operation Shows Subsynchronous Vibration, 2 and 3 Times Synchronous, and Pump Cartridge Vibration - Test 012

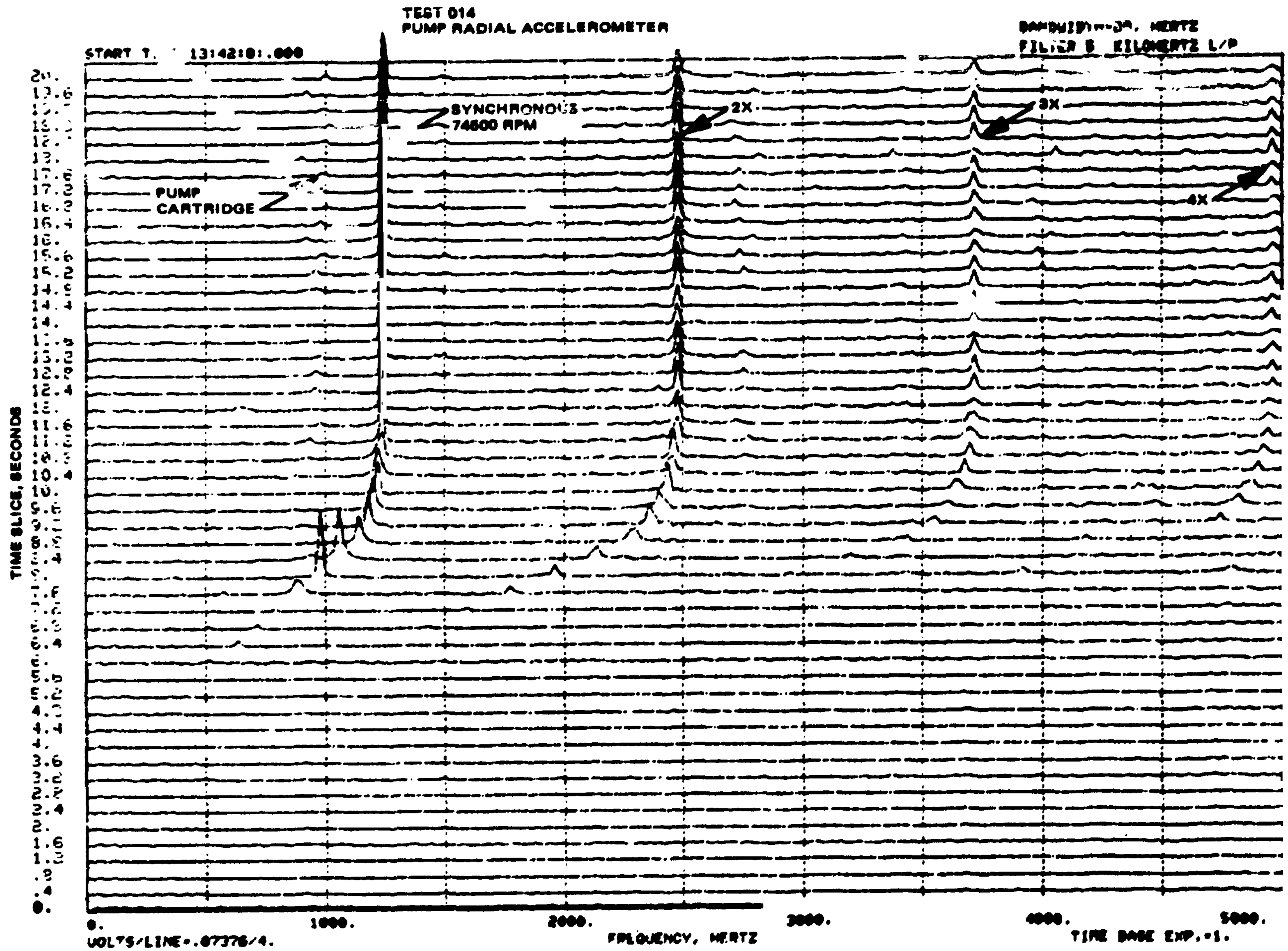

Figure 126. Synchronous Harmonics Indicating Rubbing (Also Pump Cartridge Vibration) - Test 014, Early Part of Test

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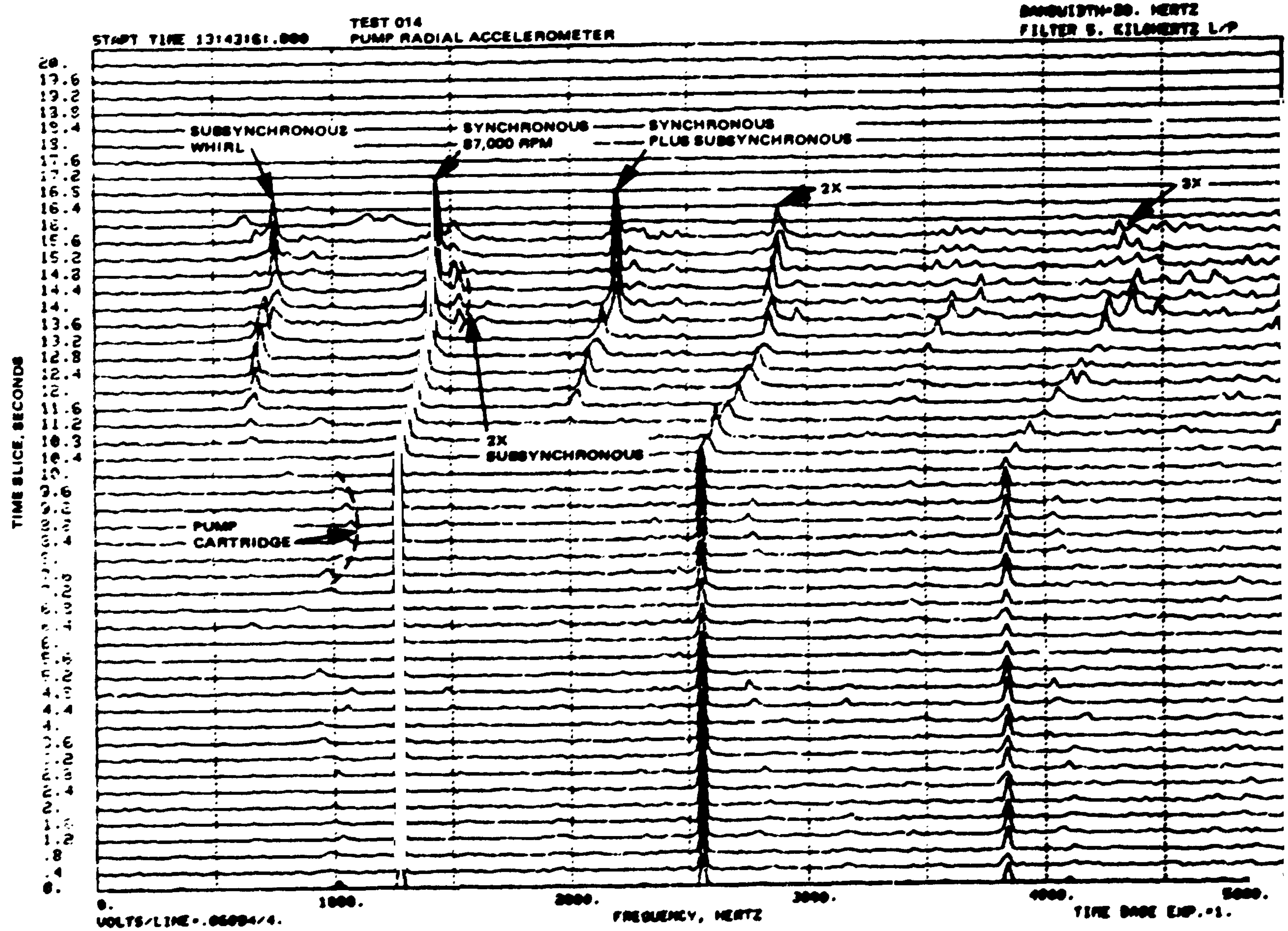

Figure 127. Synchronous and Subsynchronous Vibration With Multiple Harmonics Indicating Rubbing (Also Pump Cartridge Vibration) - Test 014, End of Test to Shutdown

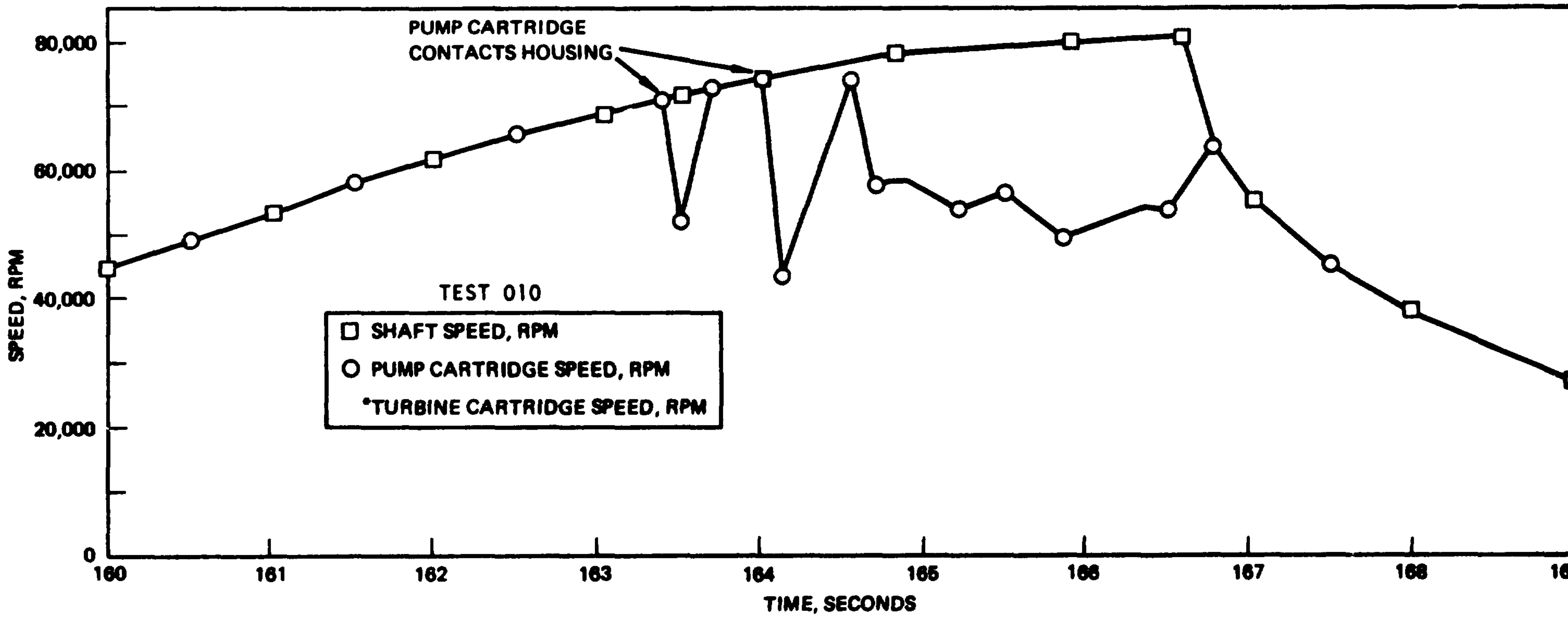

Figure 128. Shaft and Pump Cartridge Speed vs Time - End of Test 010

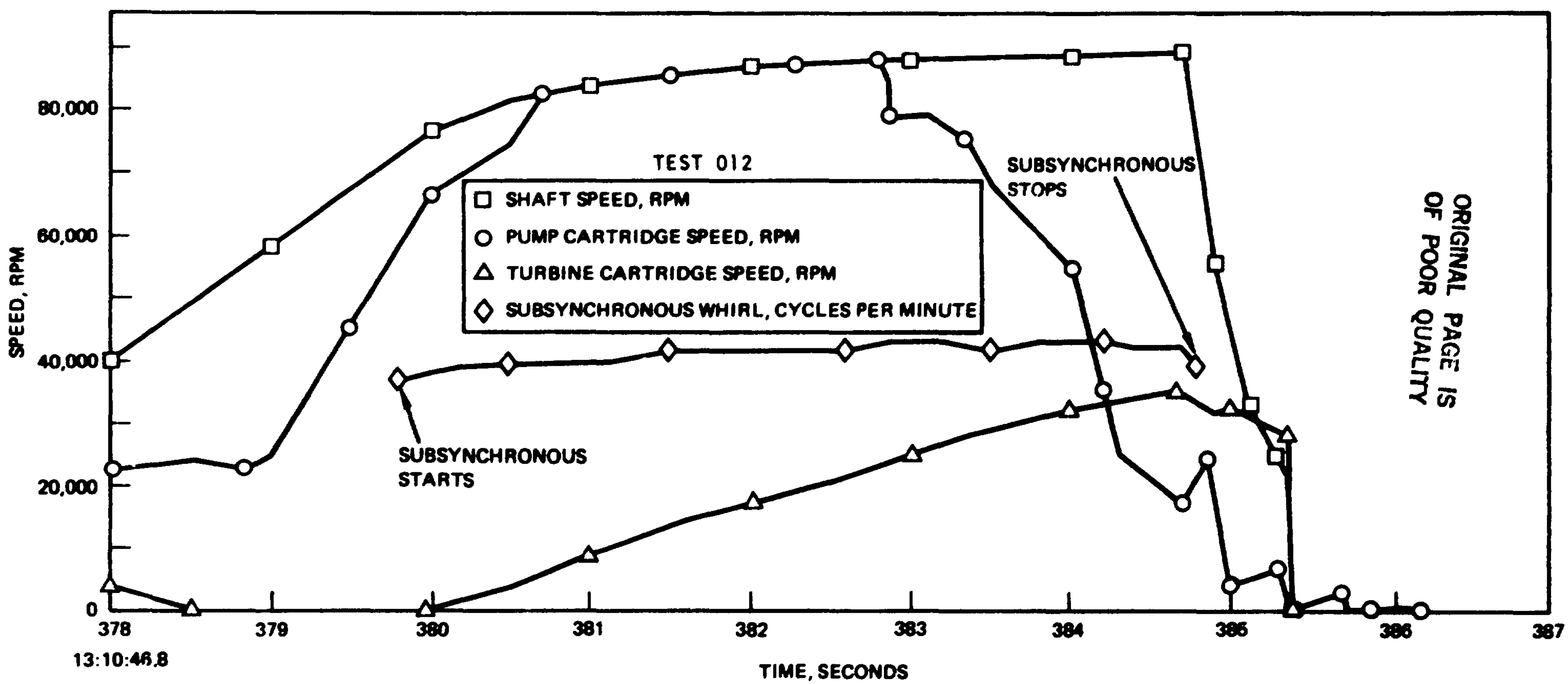

Figure 129. Shaft and Cartridge Speed Near End of Test

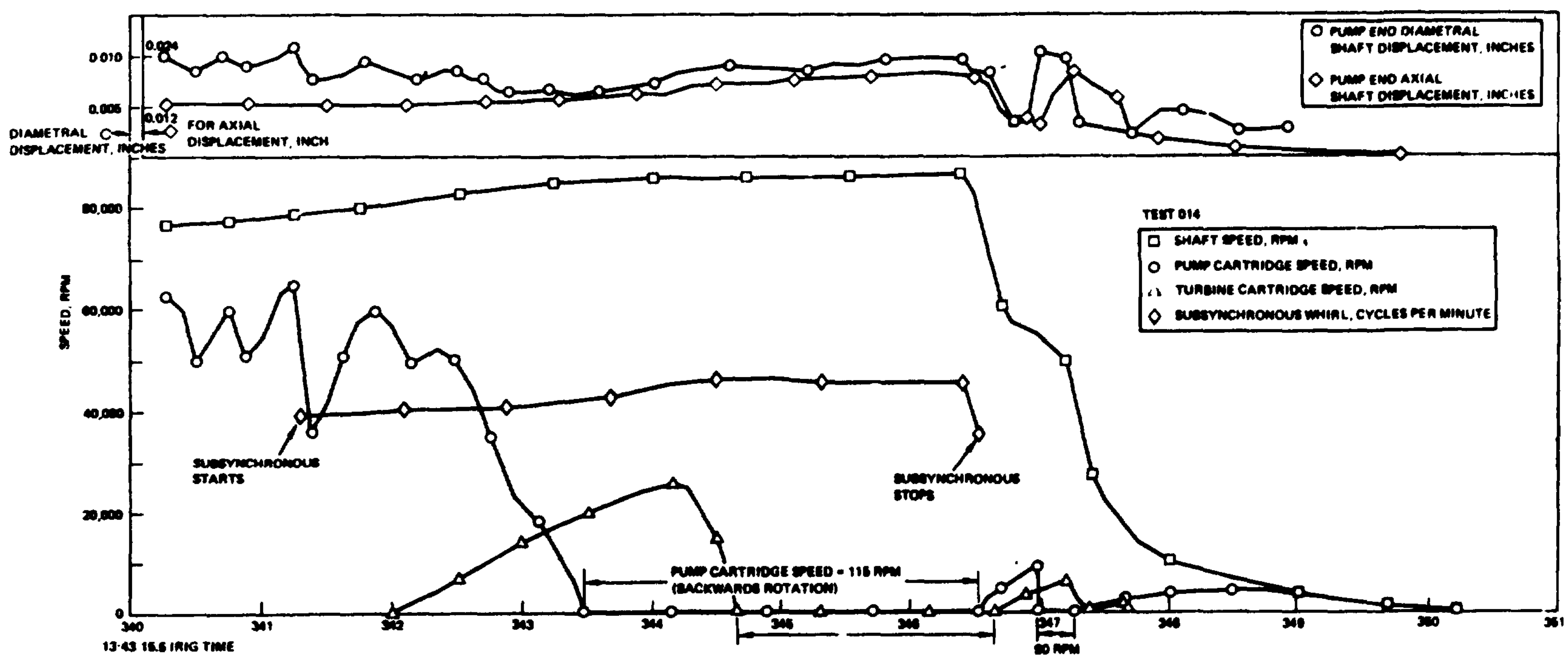

Figure 130. Shaft and Cartridge Speed and Shaft Displacment at End of Test 014

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(37,500 to 46,300 cycles per minute) and from 48.5% to 54% of pump speed. Fig. 127 shows the subsynchronous and synchronous vibration along with several harmonics in isoplot form. The problem is probably caused by excitation of the critical speed which was detected at 3665 rad/s (35,000 rpm) on previous tests. It corresponds well to the second predicted critical speed shown in Fig. 119 which should respond in the 40,000 to 45,000 cycles per minute range for a pump speed range of 7854 to 9425 rad/s (75,000 to 90,000 rpm) when bearing springrates are produced by pump-fed pressures as in tests 012 and 014.

Large vibration amplitudes were found at the high speeds. These were manifest in several forms. One was found to be synchronous, which is basically a rotor unbalance response; the other was the instability which is seen as subsynchronous whirl. An instability is not a forced vibration, such as unbalance response, but involves a mismatch of dissipative and destabilizing forces. The positive λ values of Fig. 79 relate to regions of operation where the destabilizing forces exceed the dissipative forces. In the case of the Mark 48-F turbopump, the major dissipative forces are produced by the bearing and labyrinth seals direct stiffness and damping. The destabilizing forces were produced by the labyrinth seal indirect or cross-coupling stiffness. The destabilizing forces are dependent on the tangential (couette) flow of the trapped fluid. When rotor speed reaches approximately twice the predicted second critical speed, the trapped fluid rotational speed matches that second predicted critical speed, resulting in maximization of the destabilizing forces. The result is large shaft deflections which can cause damage to the turbopump through contact of the rotor to the housing.

The subsynchronous whirl was coincident with heavy rubbing of the pump interstage labyrinth seals as indicated by the 2 and 3 times pump speed harmonics on the pump radial accelerometer shown in Fig. 125 and 127, and as measured after the pump was dismantled. Indications of similar rubbing amplitudes with 2 and 3 times pump speed harmonics occurred on earlier tests and on test 014 prior to subsynchronous vibration. This is due to the high amplitudes indicated by rotor unbalance response (synchronous vibration). The pump at disassembly showed 360-degree wear on casing impeller labyrinth stage seals. Figure 131 shows a plot of the radial shaft operating deflections necessary to wear each seal the amount measured. It also shows the hydrostatic bearings to be bound up and not able to rotate when the maximum seal wear occurred. This did in fact happen 2 to 3 seconds after whirl inception during test 014. For more information on this, see the section on general bearing cartridge performance.

Since this pump has operated in excess of 9425 rad/s (90,000 rpm) with standard ball bearings with no stability problems, this raises the question as to whether the incorporation of the hybrid bearing configuration into the turbopump resulted in the instability encountered. Test 010 reached 8514 rad/s (81,300 rpm) with the hybrid bearings and remained stable. This makes it advantageous to investigate the different running conditions between tests 010, 012, and 014.

1. Difference in Bearing Supply Pressures

   Test 010 ran higher bearing supply pressures to both the pump and turbine bearings than did tests 012 or 014 (see Table 17). However, according to the stability analysis in Fig. 79, softer hydrostatic bearings provide greater stability margin. This makes the drop in supply pressures unlikely as the cause of the instability.

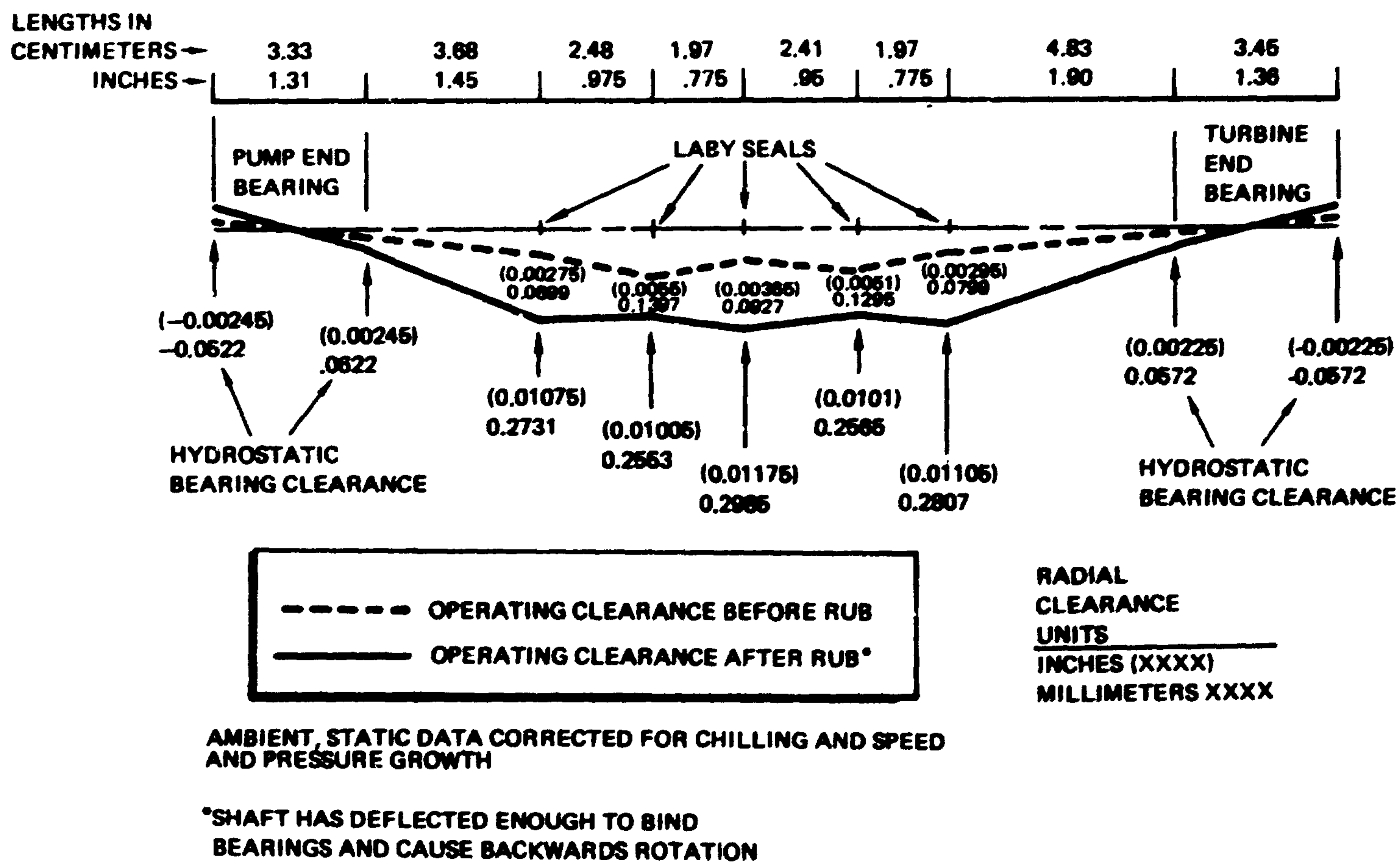

Figure 131. Labyrinth Seals Operating Radial Clearances Before and After Rub

2. Change in Turbine Pressure Ratio Which Allowed Turbine Cartridge Rotation

Various turbine-end cartridge positions have been schematically diagrammed in Fig. 132 through 135 for illustrative purposes. The turbine pressure ratio was changed between tests 010 and 012 to reduce turbine and axial shaft load which was preventing turbine cartridge rotation (see Fig. 132 and the section on general bearing cartridge performance). This allowed turbine cartridge rotation at high pump speeds for the first time during tests 012 and 014. A relationship between whirl inception and the beginning of turbine cartridge rotation can be seen when examining Fig. 129 and 130. Turbine cartridge rotation started 0.2 second after whirl inception during test 012 and 0.7 seconds after whirl inception during test 014. A possible explanation of this behavior which was reinforced by hardware inspection is shown in Fig. 133. The reduction in the axial shaft load allowed the bearing cartridge and shaft to float and tilt. This tilt caused surface-to-edge contact between the Bearium rub ring and the bearing cartridge. This contact created a polished ring on the end of the turbine cartridge (top right of Fig. 133).

The pump cartridge was also tilting with the shaft bow as shown in Fig. 134. Evidence of this was found when the pump was dismantled and it was discovered that some of the silver plating on the inlet end of the bearing support had been either relocated inward or rubbed away (see Fig. 135).

Subsynchronous whirl starts just at the beginning of turbine cartridge rotational freedom, as shown in Fig. 129 and 130. The whirl also begins during the pump cartridge acceleration on test 012. With the pump cartridge speedup, the stiffness and damping is increased at the same pressure levels by the increase in cartridge speed and clearance. Similarly, the turbine-end cartridge speed increase results in an increased stiffness and damping due to decreased clearances. This agrees with the general conditions shown in Fig. 79 where increased stiffness and damping causes stability margin decrease. The instability cannot be directly calculated or predicted by rotordynamic analysis for this operating condition due to the complex manner of the changes in the various parameters. It is important to note that the stability margins of the turbopump could be enhanced by the use of straight seals in the place of labyrinth seals. Although the leakage rate may be compromised, there is an increased stiffness and damping available by these modifications which were not in the scope of the present contract. It is recommended this be considered for future turbopump designs where stability is marginal. Recent studies have brought to light the possibility that bearing tilt or angulation through the supporting hydrogen film could produce destabilizing forces (Ref. 16). The bending modes occurring at the high speeds may have caused the shaft bending forces to develop bearing angulation sufficient to create this condition.

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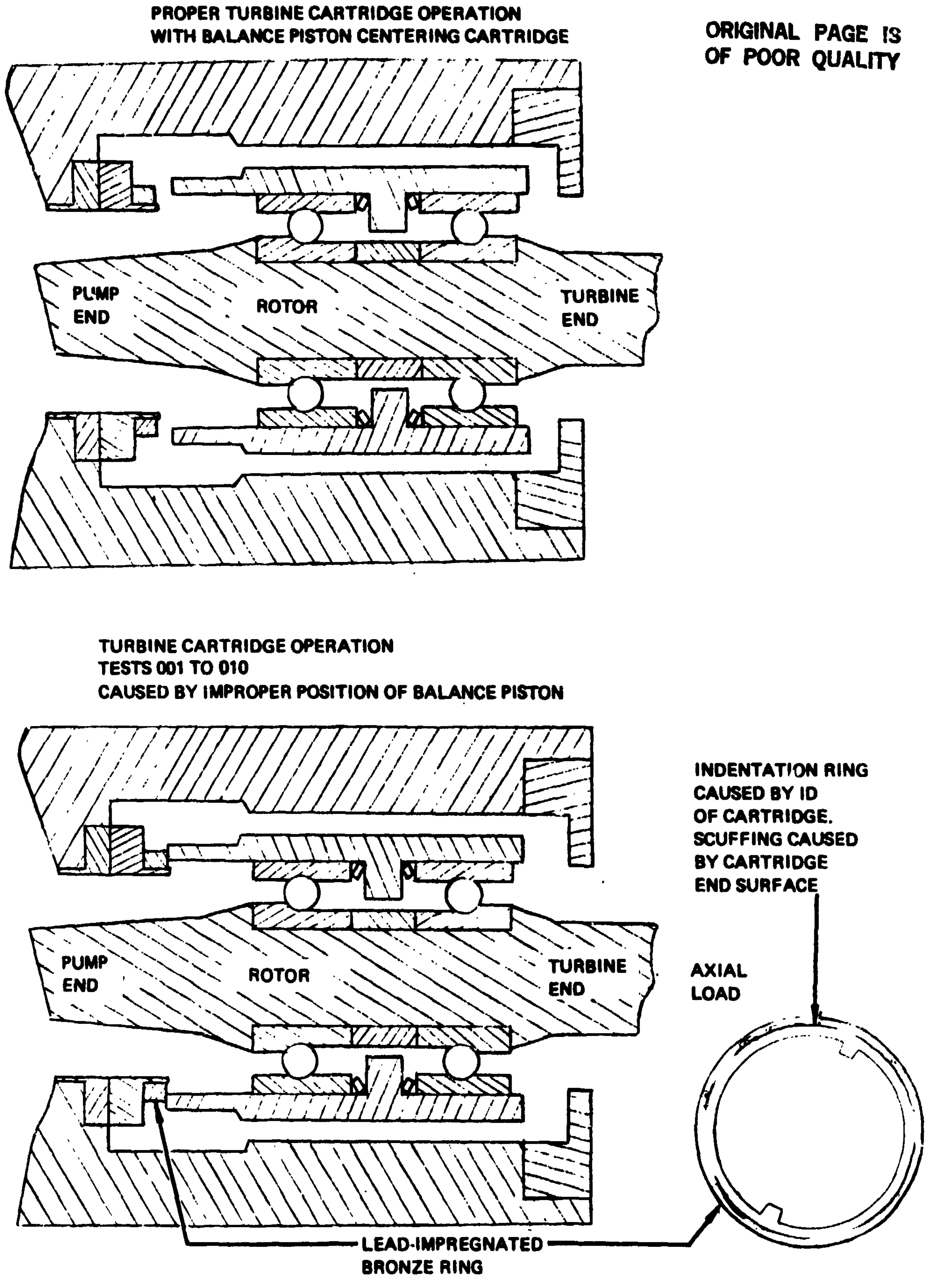

Figure 132. Turbine Cartridge Position as Function of Balance Piston

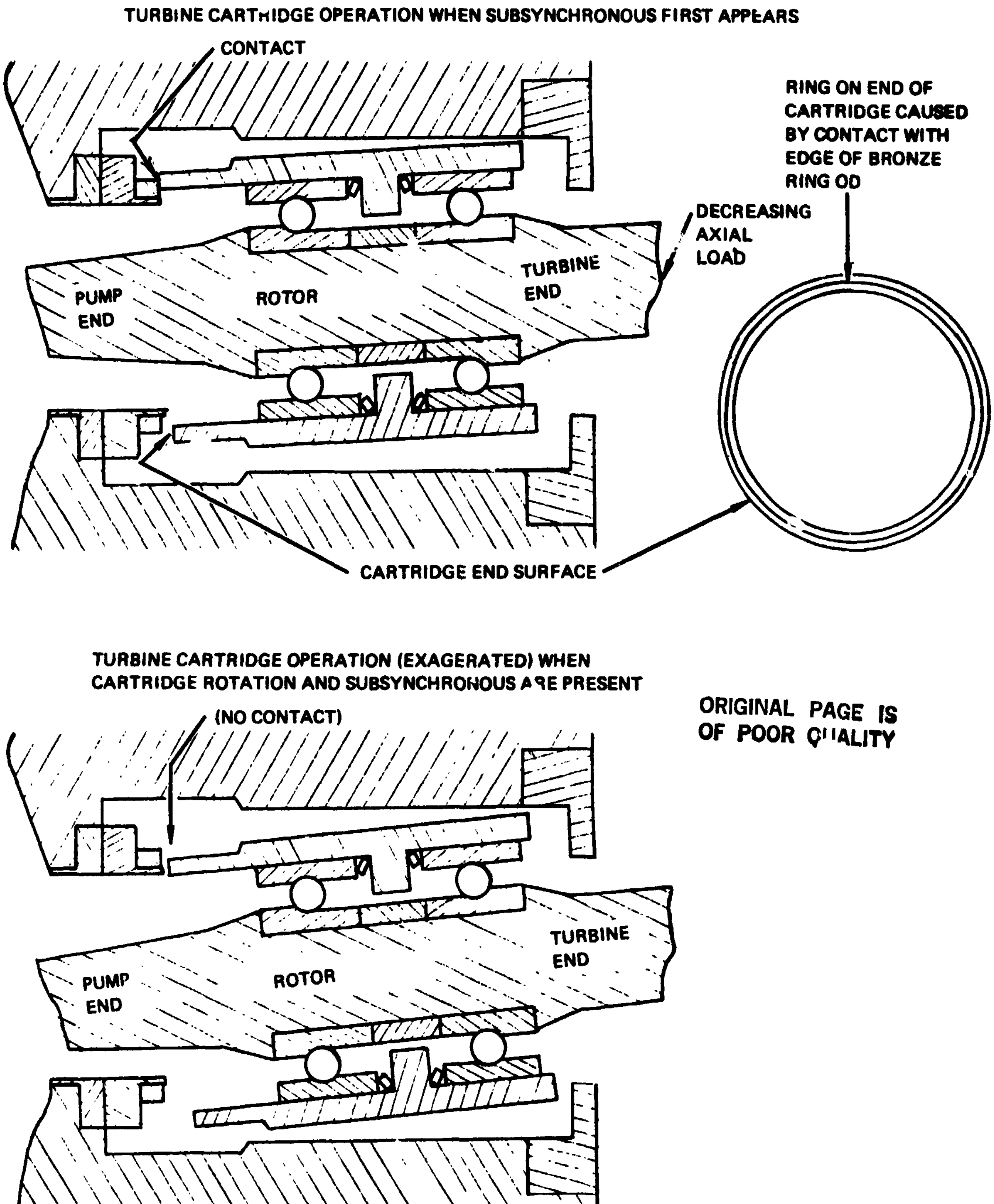

Figure 133. Turbine Cartridge Position During Subsynchronous Vibration Levels

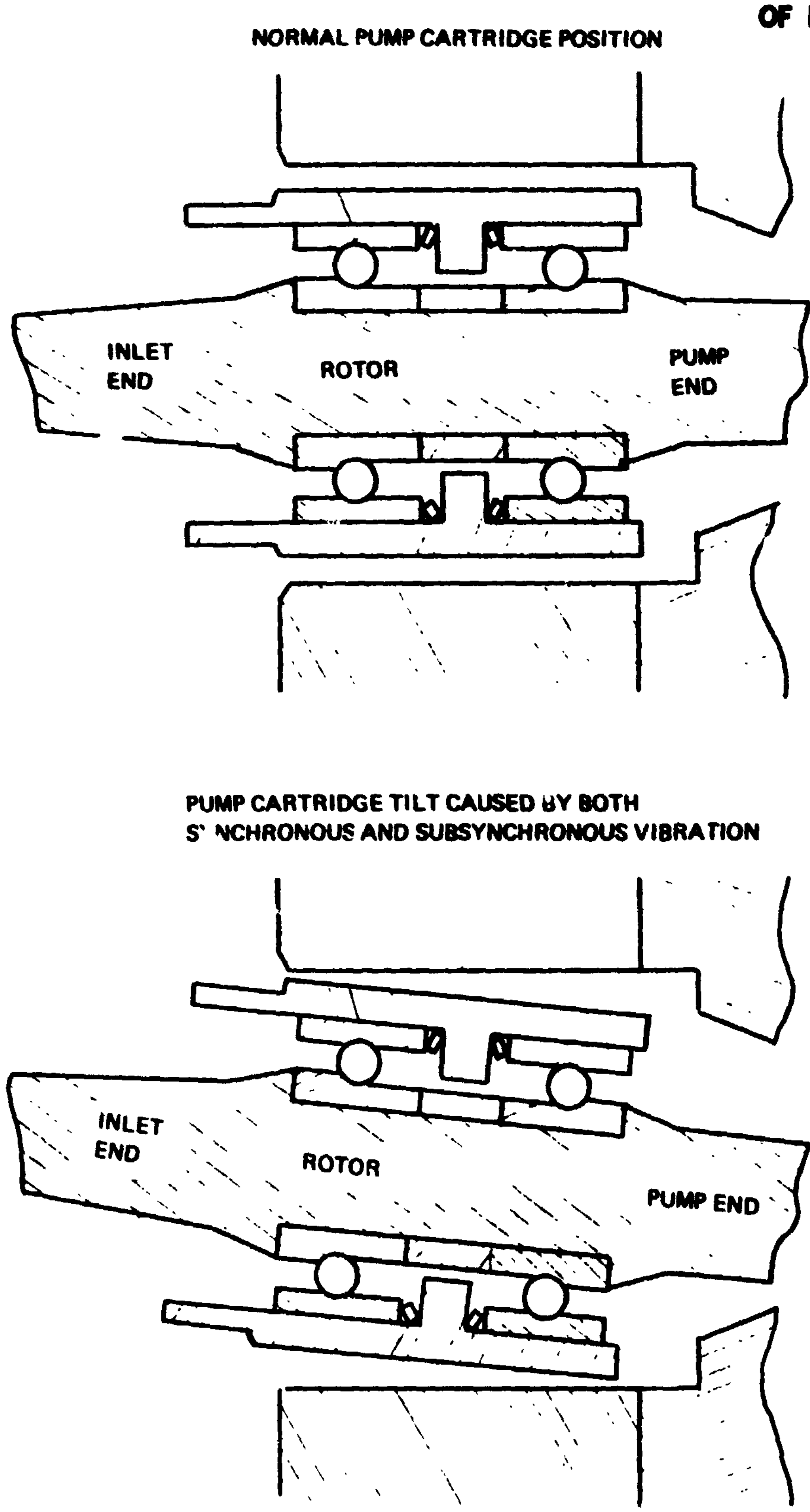

Figure 134. Pump-End Cartridge [illegible] With Rotor Bending

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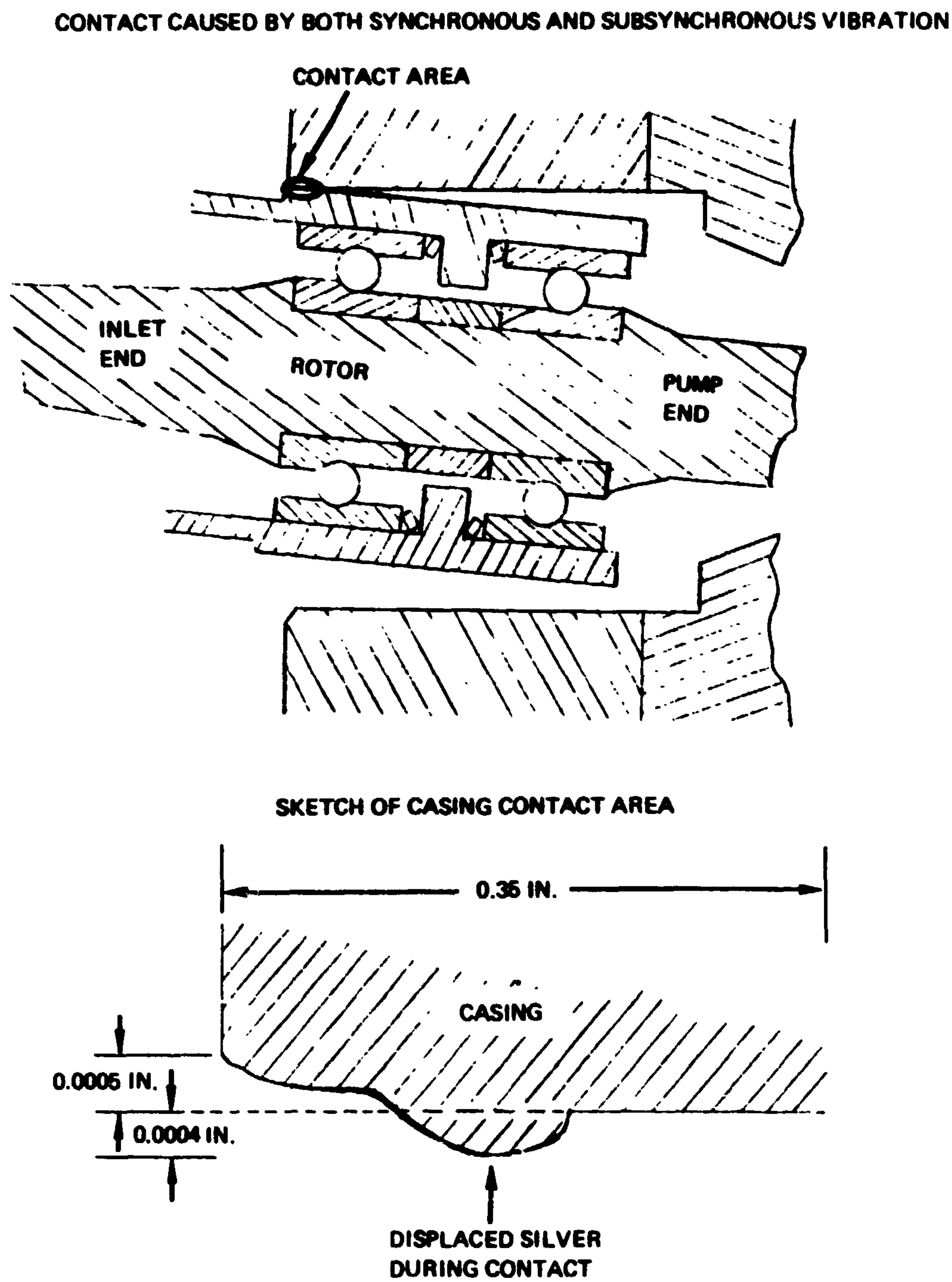


Figure 135. Displaced Silver Plating on Pump-End Bearing

Synchronous Harmonics of Shaft Speed

1. Exact Multiples of Shaft Speed

Harmonics which were exact multiples of shaft speed were clearly detectable on tests 008, 010, 012, and 014. All four tests showed 2 and 3 times synchronous vibration above 6283 rad/s (60,000 rpm), and test 014 showed 4 times synchronous (see Fig. 123 through 127). When subsynchronous whirl appeared during tests 012 and 014, the harmonics persisted. Pump disassembly showed that these harmonics were indications of interstage labyrinth seal rub. These seals show rubbing at all times during operation above 6283 rad/s (60,000 rpm) and most heavily during subsynchronous whirl. The hybrid bearings alone were apparently unable to limit the shaft bending mode amplitudes sufficient to prevent seal damage. It is not logical to assume that these bearings alone could prevent this due to the relatively large midspan of the rotor between the bearings. Other damping devices such as straight, smooth seals in place of the labyrinth seals would provide adequate damping of these amplitudes.

2. 3/2 Harmonics of Shaft Speed

During tests 006 and 007, a very unusual 3/2 multiple of shaft speed was detected on the turbine end of the pump when shaft speed was about 3456 rad/s (33,000 rpm). This is shown in Fig. 136 and 137, and no explanation for this frequency has been determined. However, it should be noted that when this harmonic appeared, the pump was operating just below a 3665 rad/s (35,000 rpm) critical speed, which was detected during later tests (see section on critical speeds). The frequency was not evident on shaft Bently data and the tracking of shaft speed indicates a rotor phenomena rather than a casing resonance.

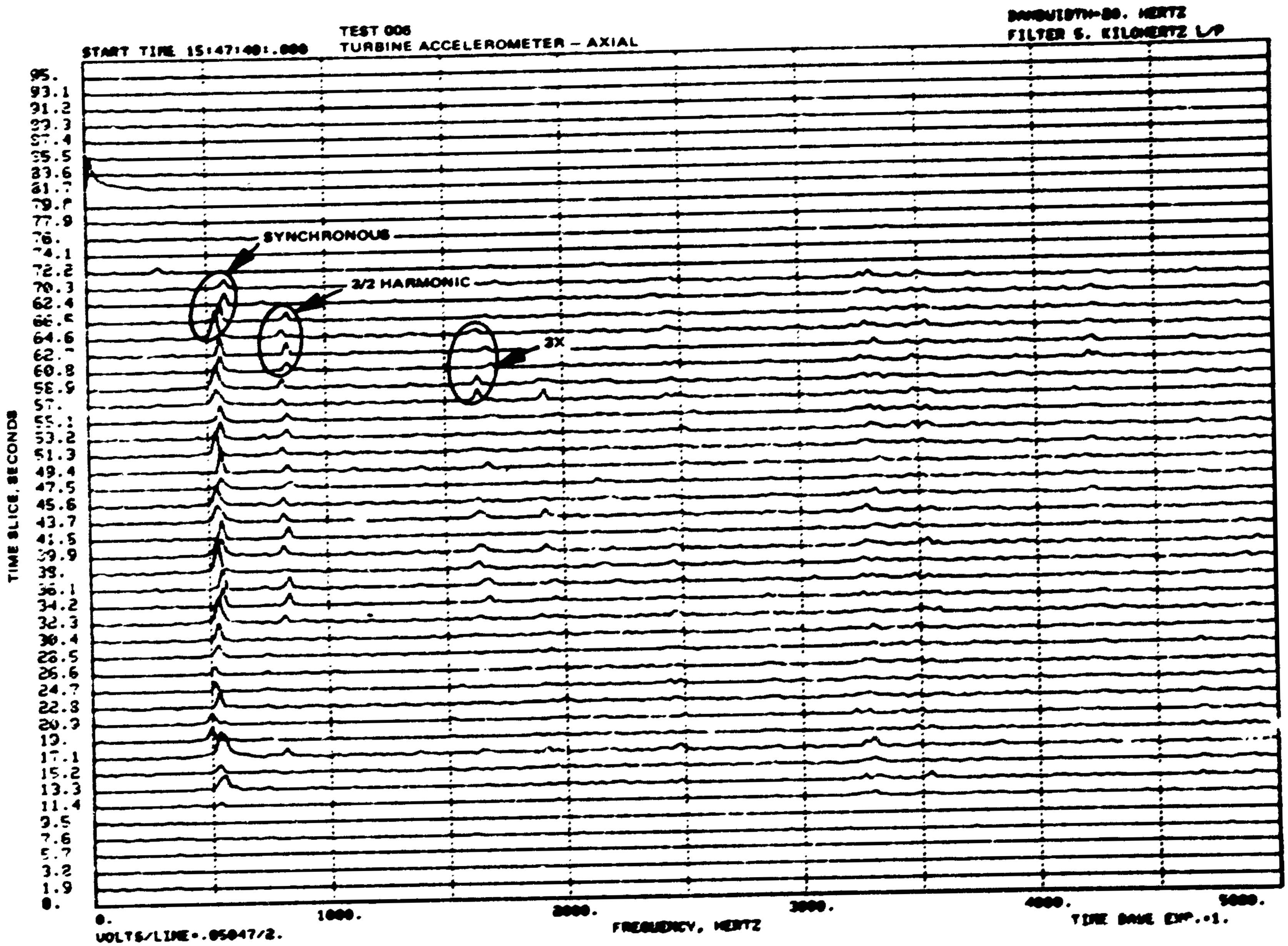


Figure 136. 3/2 Harmonic On Turbine Axial Accelerometer - Test 006

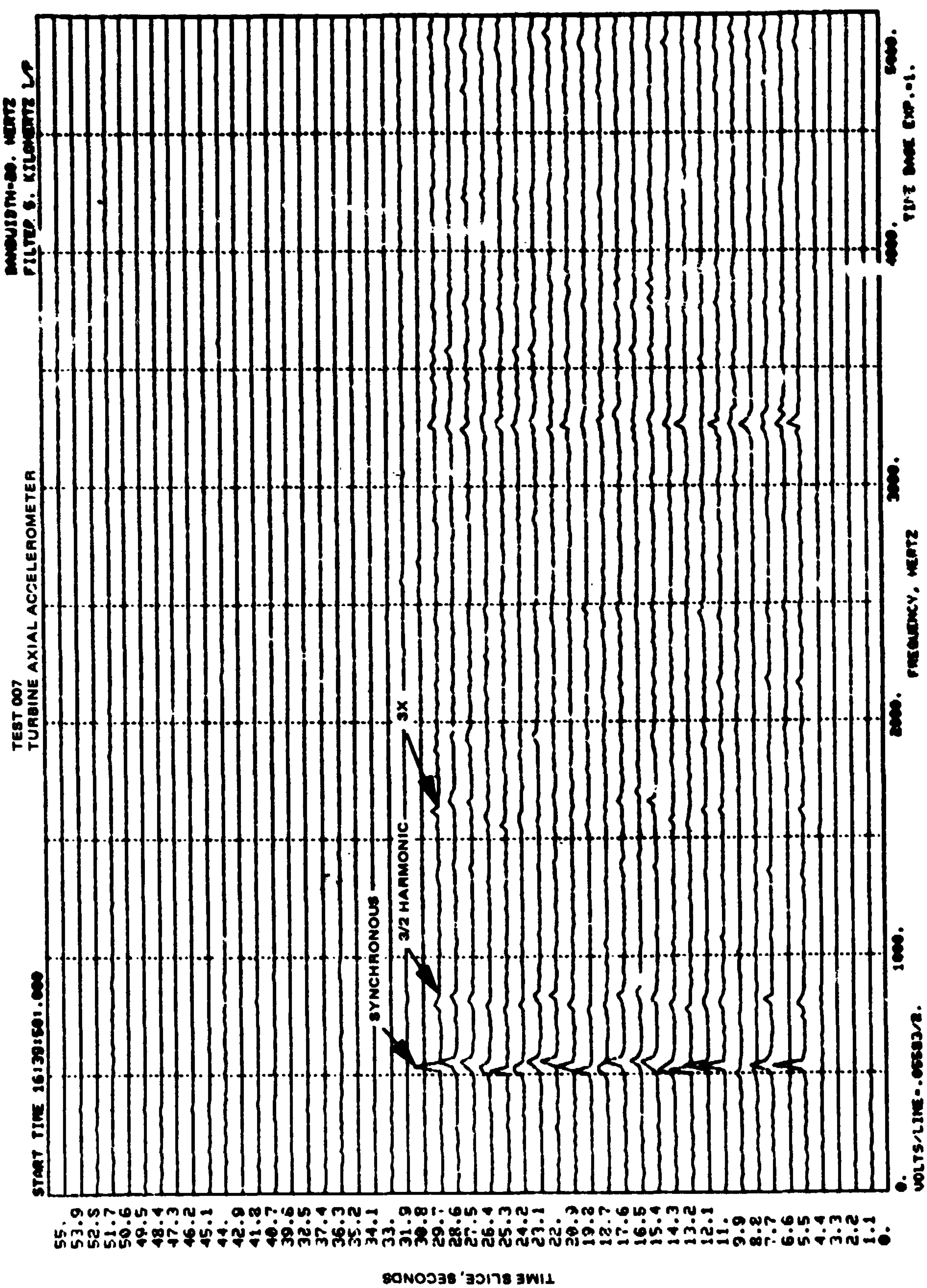


Figure 137. 3/2 Harmonic On Turbine Axial Accelerometer - Test 007

General Bearing Cartridge Performance

1. Pump Cartridge Performance

   The pump end hydrostatic bearing cartridge performed very well in the 0 to 6807 rad/s (0 to 65,000 rpm) range for all tests. It tracked pump speed during steady state operation and followed closely during pump accelerations and decelerations. However, when the pump was operated in the 6807 to 9425 rad/s (65,000 to 90,000 rpm) range, the shaft radial deflections and angulation combined to cause contact between the cartridge and the bearing support (see Fig. 99, 100 and, 135). The cartridge would then slow down and speed up repeatedly until there was established a new steady state speed at some fraction of shaft speed. This relationship also can be seen in Fig. 128, 129, and 130 where both shaft and cartridge speed are plotted. Evidence of this rubbing was discovered during teardown in the form of a small amount of silver plating that had been removed or displaced inward on the inlet end of the bearing support (see bottom of Fig. 135).

   When the pump cartridge would operate below pump speed but above 6283 rad/s (60,000 rpm), its own vibration signature could be seen as shown in Fig. 125 for test 012 and in Fig. 126 and 127 for test 014. Its speed would also influence shaft radial displacement as can be seen in Fig. 130 where cartridge and shaft speed are plotted along with diametral shaft displacement.

2. Turbine Cartridge Performance

   During tests 001 through 010, the turbine cartridge failed to turn due to inadequate balance piston position. The shaft was moving axially toward the inlet during startup as shown by the axial displacement plot in Fig. 138 and 48. This movement, which was measured by an axial proximity probe on the pump end, caused the turbine bearing cartridge to press against the Bearium ring which prevented rotation (see bottom of Fig. 132). Slight rubbing marks on the Bearium ring discovered during teardown verifies this contact.

   A partial solution to freeing the turbine cartridge was by changing the turbine pressure ratio. The turbine pressure ratio was increased to counterbalance the axial load on the turbine bearing and reposition the shaft so that the turbine cartridge would float between its end stops. This resulted in turbine cartridge rotation at a fraction of pump speed during tests 012 and 014. Figure 129 shows turbine cartridge rotation beginning for test 012 when a pump speed of 8011 rad/s (76,500 rpm) is reached and steadily increasing to a maximum of 3665 rad/s (35,000 rpm) before the test was cut. Figure 130 shows similar results for test 014 until both turbine and pump cartridge rotation are stopped by large shaft deflections. This flexure caused bearing cartridge contact and has been determined to have resulted in a backward rotation of the cartridges (see next section).

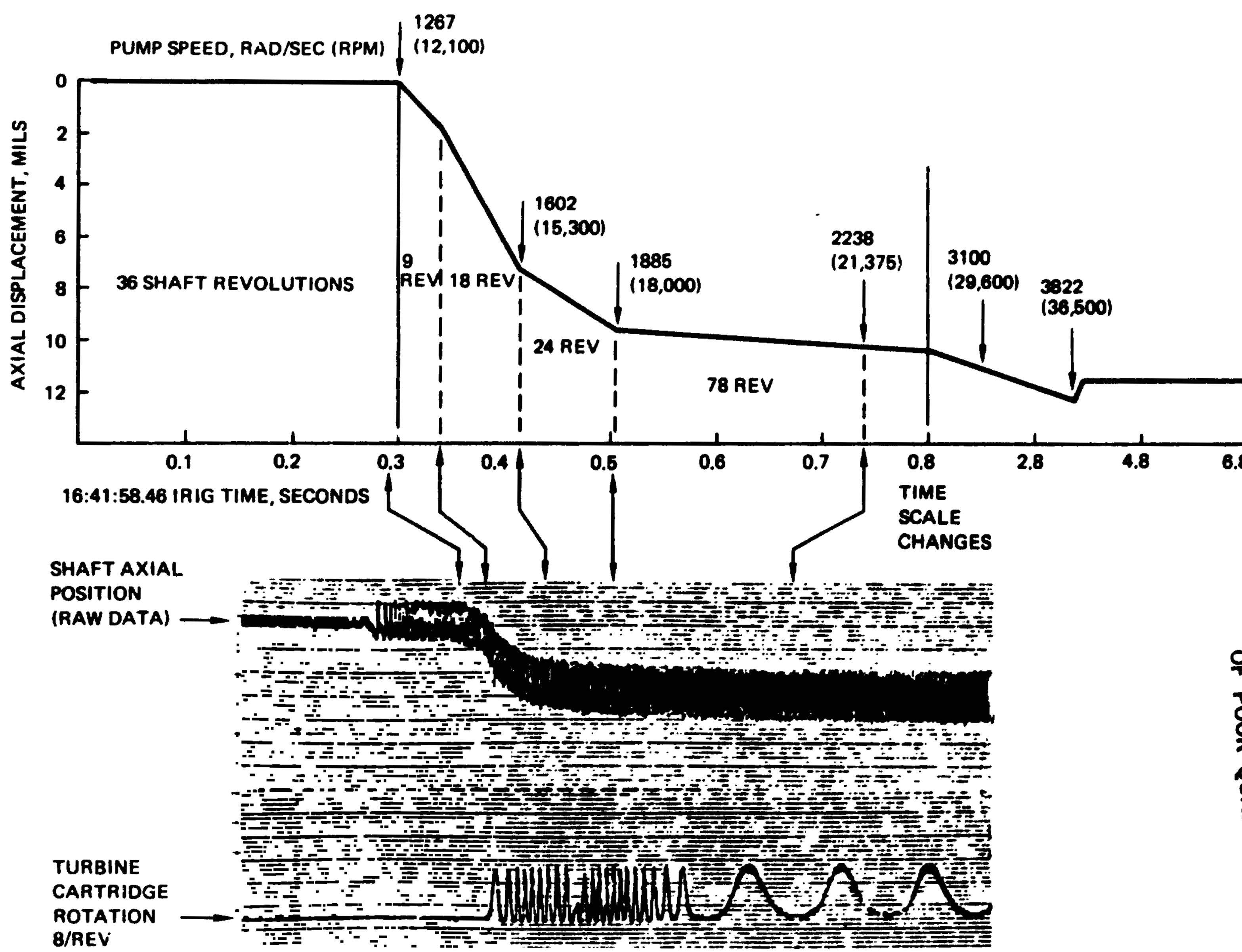


Figure 138. Balance Piston - Shaft Axial Movement at Startup - Test 010

3. Backward Rotation of Cartridges

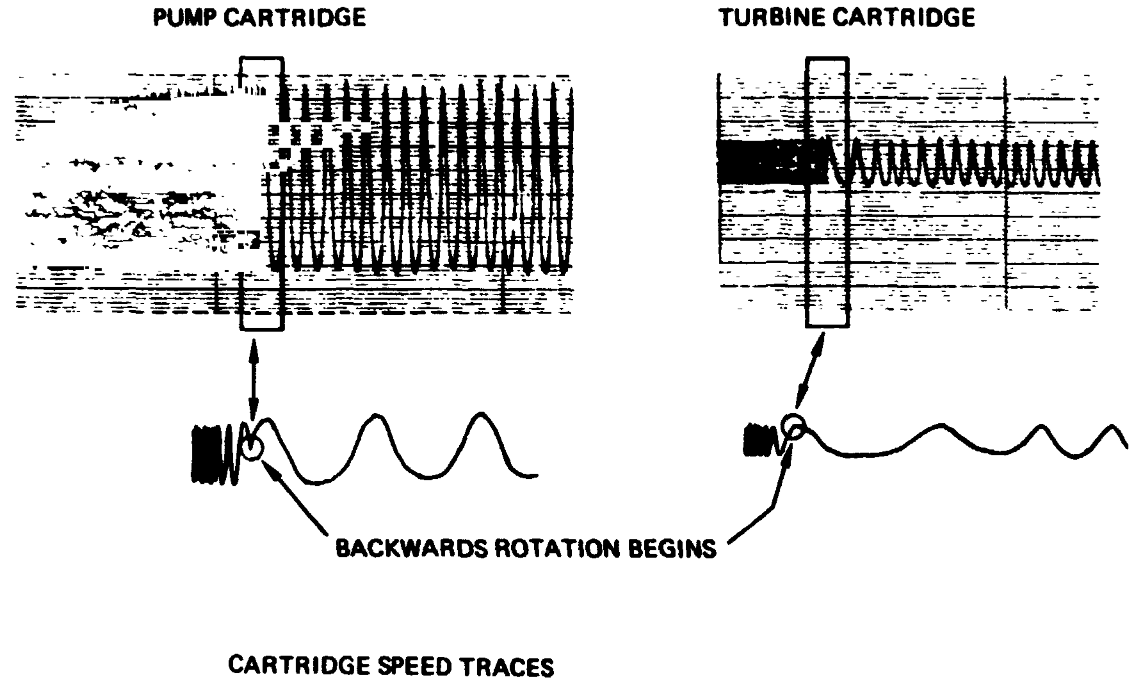
When subsynchronous whirl was encountered during test 014, shaft bow was of such a magnitude as to eventually bind both hydrostatic bearing cartridges. This is shown graphically in Fig. 131 where measured seal wear has been used to make a bowed rotor plot. Figure 130 shows the pump cartridge and turbine cartridge stopping 2.2 and 3.4 seconds, respectively, after the instability appears. This binding produced a slow backward rotation of each cartridge dependent on the relative diameters of the cartridges and bearing supports and the subsynchronous vibration frequency. Evidence of the beginning of backward rotation can be seen in the top of Fig. 139, which shows the wave form from each cartridge speed probe when rotation reverses. The bottom of Fig. 139 shows the mechanism involved using synchronous vibration as the force causing cartridge-to-support contact. Figures 140 and 141 show the calculation of backward rotation speed for both cartridges using the synchronous and subsynchronous frequencies from test 014 as the driver. Comparison with the measured speeds indicate that the subsynchronous vibration was the principle driver maintaining cartridge-to-support contact 12.3 rad/s (118 rpm) measured and 12.7 rad/s (121 rpm) calculated for the pump-end bearing, and 10.2 to 15 rad/s (97 to 143 rpm) measured and 11.6 rad/s (111 rpm) calculated for the turbine-end bearings).

Rotordynamic Analysis Conclusions

1. Comparison of the critical speeds detected during testing with the analytical predictions was hampered by the turbine end cartridge unknown spring rate due to axial loading. It was determined, however, that the two critical speeds detected did correspond to the second and third analytical shaft modes.

2. A subsynchronous whirl was encountered on this turbopump at high speeds with the internally supplied flow conditions. The frequency of whirl varied from 47 to 54% of shaft speed and corresponds well to the second predicted critical speed. Rotordynamic prediction of this instability in advance was not possible due to the nature of the hydrostatic bearing and shaft speed differences encountered in the tests. Improvement in the stability margin can be achieved on a rotor design of this type by the addition of damping in the rotor midspan at the seals. This turbopump modification will provide stiffness and damping all along the midspan of the rotor and not force the hybrid bearings to assume all the responsibility for damping.

3. The hybrid bearing rotor assembly could not sufficiently control synchronous radial shaft deflections due to rotor unbalance or misalignment when rotor speed exceeded 7330 rad/s (70,000 rpm). This, again, may have been due to a lack of stiffness and damping along the midspan of the rotor.



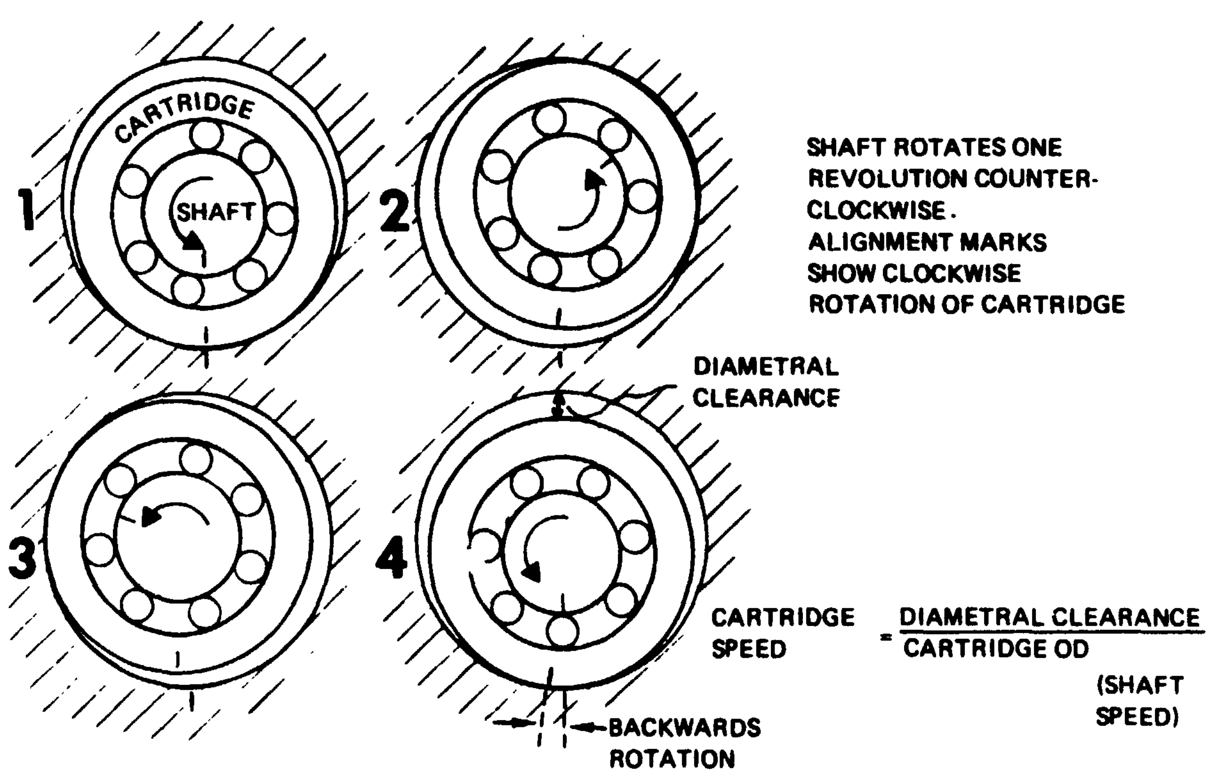
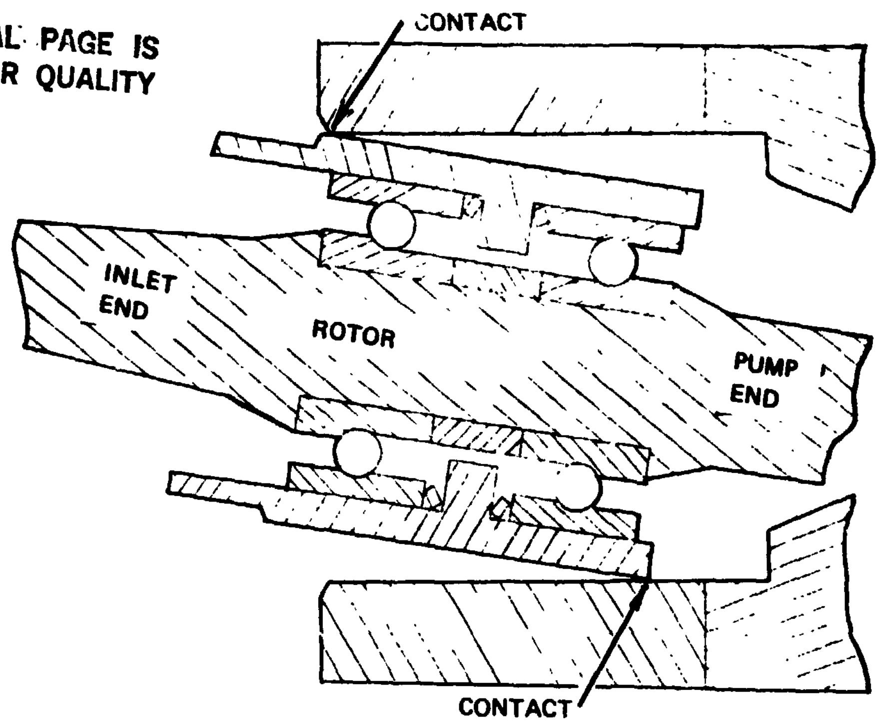


Figure 139. Mechanism of Cartridge Backward Rotation



CALCULATED SPEED

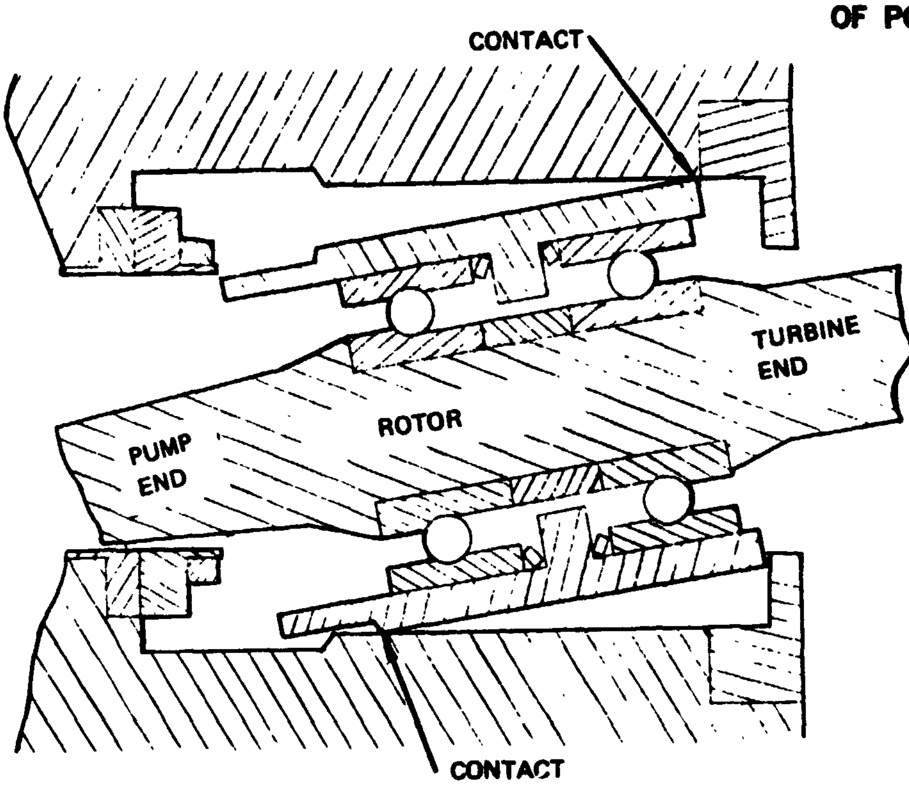
SHAFT SPEED = 9006 rad/sec (86,000 RPM)
DIAMETRAL CLEARANCE = (0.0049 INCH) 0.1245 mm
BEARING ID = (1.744 INCH) 4.430 cm
CARTRIDGE OD = (1.7391 INCH) 4.417 cm

CARTRIDGE SPEED WITH SYNCHRONOUS DRIVER $= \frac{(0.0049)}{(1.7391)}$ (86,000) = (242 RPM) 25.3 rad/s

CARTRIDGE SPEED WITH SUBSYNCHRONOUS DRIVER $= \frac{(0.0049)}{(1.7391)}$ (43,000) = (121 RPM) 12.7 rad/s

MEASURED CARTRIDGE SPEED = (118 RPM) 12.4 rad/s

Figure 140. Pump-End Cartridge Backward Rotation



CALCULATED SPEED

SHAFT SPEED = 9006 rad/sec (86,000 RPM)
DIAMETRAL CLEARANCE = (0.0045 INCH) 0.1143 mm
BEARING I.D. = (1.744 INCH) 4.430
CARTRIDGE O.D. = (1.7395 INCH) 4.418 mm

CARTRIDGE SPEED WITH SYNCHRONOUS DRIVER $= \frac{(0.0045)}{(1.7395)}$ (86,000) = (222 RPM) 23.2 rad/sec

CARTRIDGE SPEED WITH SUBSYNCHRONOUS DRIVER $= \frac{(0.0045)}{(1.7395)}$ (43,000) = (111 RPM) 11.6 rad/sec

MEASURED CARTRIDGE SPEED = (97 TO 143 RPM) 10.2 TO 15.0 rad/sec

Figure 141. Turbine-End Cartridge Backward Rotation

4. The balance piston was incapable of controlling shaft axial movement well enough to permit proper turbine bearing operation. This was caused by rubbing of the high-pressure orifice at startup on initial tests. The rubbing wore the high-pressure orifice (Fig. 58) so that the shaft was required to operate further forward toward the pump end. This caused the turbine cartridge end to contact the forward stop and prevent rotation. This result caused the operating conditions not to conform to those used in the rotordynamic predictions, thereby making direct correlations without further analytical effort impractical.

Rotordynamic Analysis Recommendations

1. All analytical work done previously assumed cartridge rotation for both bearings. The location of the critical speeds for the combined condition of unnaturally high bearing supply pressures and the axially loaded turbine end bearing should be determined analytically, if possible, and compared to the test results.

2. Further study should be made to measure or calculate the difference in the resistance to shaft tilt or angulation between duplex ball bearings and hydrostatic bearings.

3. The stability analysis should be studied to determine why the instability encountered at 8168 rad/s (78,000 rpm) was not predicted to occur until 12,566 rad/s (120,000 rpm). Stability analysis is dependent on the direct and cross-coupled coefficients predicted for the model. Questions arise as to the accuracy of predicted values which must be verified by testing. The analysis should then be re-evaluated to match test results. This may require considerable in-depth analysis due to the lack of turbine cartridge rotation during whirl inception. The possibility of bearing cartridge tilt or angulation adding to the destabilizing forces is also a question that should be addressed (Ref. 16). In the design of a turbopump of this type, damping need not be provided exclusively at the bearings.

4. In a turbopump of this type, with a large span between bearings, the possibility of using straight, smooth seals in place of the labyrinth seals to control shaft deflection should be seriously considered. Any pump assembled with hybrid bearings in the future should have evaluated the use of damping-type, straight, smooth pump interstage seals. The added damping inherent in this type of seal would be placed at the ideal locations for maximum effectiveness and would provide greater stability margin without a singular reliance on the hybrid bearing only to achieve this result.

Turbopump Performance - Turbine

During testing of the hybrid bearing turbopump, the turbine working fluid was gaseous hydrogen. The turbine pressure ratio was increased between several tests by reducing the exhaust system resistance. This was to increase turbine axial thrust, which was required to unload the turbine hydrostatic bearing cartridge to permit cartridge rotation.

The tests were conducted in the following three series:

1. Tests 001 to 010 were run with target speeds from 2618 to 8378 rad/s (25,000 to 80,000 rpm), total-to-total pressure ratio of 1.45, and 9 holes in the turbine exhaust orifice.

2. Test 011 was run with target speeds of 4712 to 6807 rad/s (45,000 to 65,000 rpm), total-to-total pressure ratio of 2.0, and 13 holes in the turbine exhaust orifice.

3. Tests 012 and 014 were run with target speeds of 4712 to 9425 rad/s (45,000 to 90,000 rpm), total-to-total pressure ratios 2.5 and 2.95, and 17 holes in the turbine exhaust orifice.

The analysis was performed for each point for a range of turbine speeds from 6283 to 9425 rad/s (60,000 to 90,000 rpm) at steady-state condition, and the total-to-total pressure ratios from 1.45 to 2.95, and based on tests 008, 012, and 014 which achieved over 6283 rad/s (60,000 rpm).

Turbine efficiency could not be determined accurately because the effects of the hydrostatic bearing flows, overboard flows, and turbine seal leakage on turbine output power could not be evaluated accurately. Turbine power calculated from the measured turbine temperature drop was not representative either, because the turbine seal leakage into the turbine reduced the measured turbine outlet temperature.

An estimate of turbine output power was made which partially accounted for the hydrostatic bearing flows. The estimate gave an approximate indication of the turbine efficiency trends for operation at the higher turbine pressure ratios (design pressure ratio equalled 1.443 total-to-total). Turbine output power was estimated from the pump hydraulic power divided by the measured pump isentropic efficiency. Pump hydraulic power was modified to partially account for the power costs from the hydrostatic bearing flow.

Test 008 was run with the external hydrostatic bearing supply system. Hydraulic power was not affected by the pump-end bearing external supply because the system had an external supply and drain. Hydraulic power was affected by the turbine bearing external flow system because the measured bearing flow was drained into the second-stage impeller inlet and passed through the second and third pump stages and was included in the discharge venturi measured flow. The actual hydraulic power was reduced by the turbine bearing flow multiplied by one-third of the pump overall head rise for the first-stage impeller that did not pump the turbine bearing flow.

Tests 012 and 014 were run with the internal hydrostatic bearing supply system. The pump-end bearing flow was tapped off downstream of the first-stage impeller, was measured, then passed through the hydrostatic bearing to an overboard drain. The first-stage pump flow was then the measured discharge flow plus the measured pump-end bearing flow. Pump hydraulic power was adjusted for the pump-end bearing flow through the pump first stage. The turbine-end hydrostatic bearing flow was tapped-off downstream of the pump discharge, but upstream of the discharge flow measuring venturi. After passing through the hydrostatic bearing, it was drained into the second-stage impeller inlet. The recirculated turbine bearing flow added heat to the measured discharge flow, which is accounted for in the pump measured isentropic efficiency as with the balance piston recirculated flow. The hydraulic power was not adjusted for the turbine bearing flow.

Turbine efficiency data using the estimated absorbed power discussed above and the available turbine power were plotted in Fig. 142. The turbine calibration curve characteristic is shown referenced to the test 008 average point. Test 008 was near the turbine design pressure ratio. An efficiency decrease is shown for the higher pressure ratio tests in Fig. 142.

An efficiency ratio was formed in Fig. 143 to compare the estimated test performance with the calibration curve characteristic using the test 008 point near the design pressure ratio as the reference. An efficiency decrease of 4% is shown at a pressure ratio of 2.54. A 15% decrease is shown for a pressure ratio of 2.95.

Turbine performance would tend to decrease with increasing pressure ratio beyond the design value due to higher loading and Mach numbers in the blading. The turbine tip seals and interstage seals were found damaged by rubbing during post-test turbopump disassembly. Turbine seals damage would also reduce efficiency and

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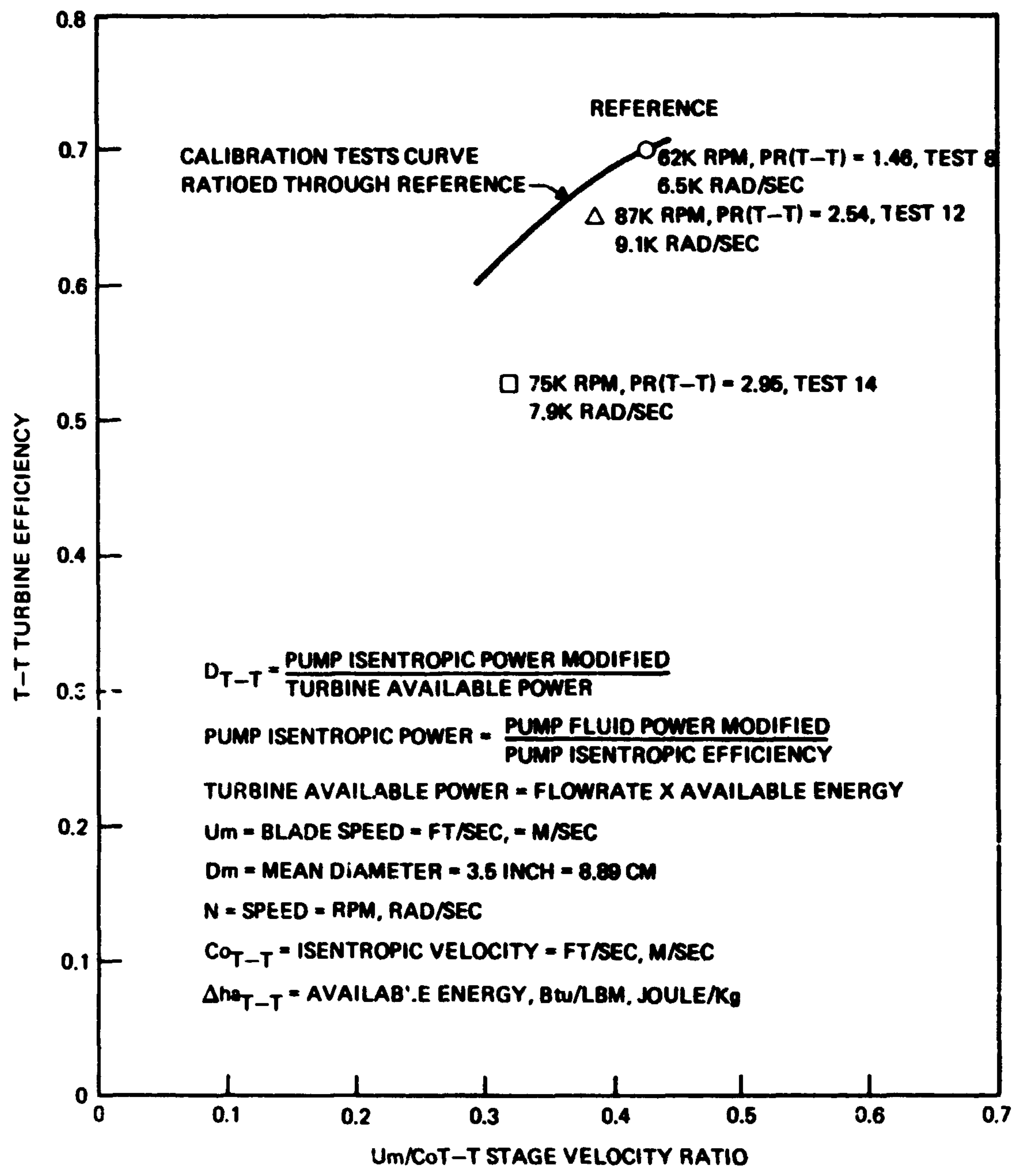

Figure 142. Mark 48-F Turbine Test Performance Comparison

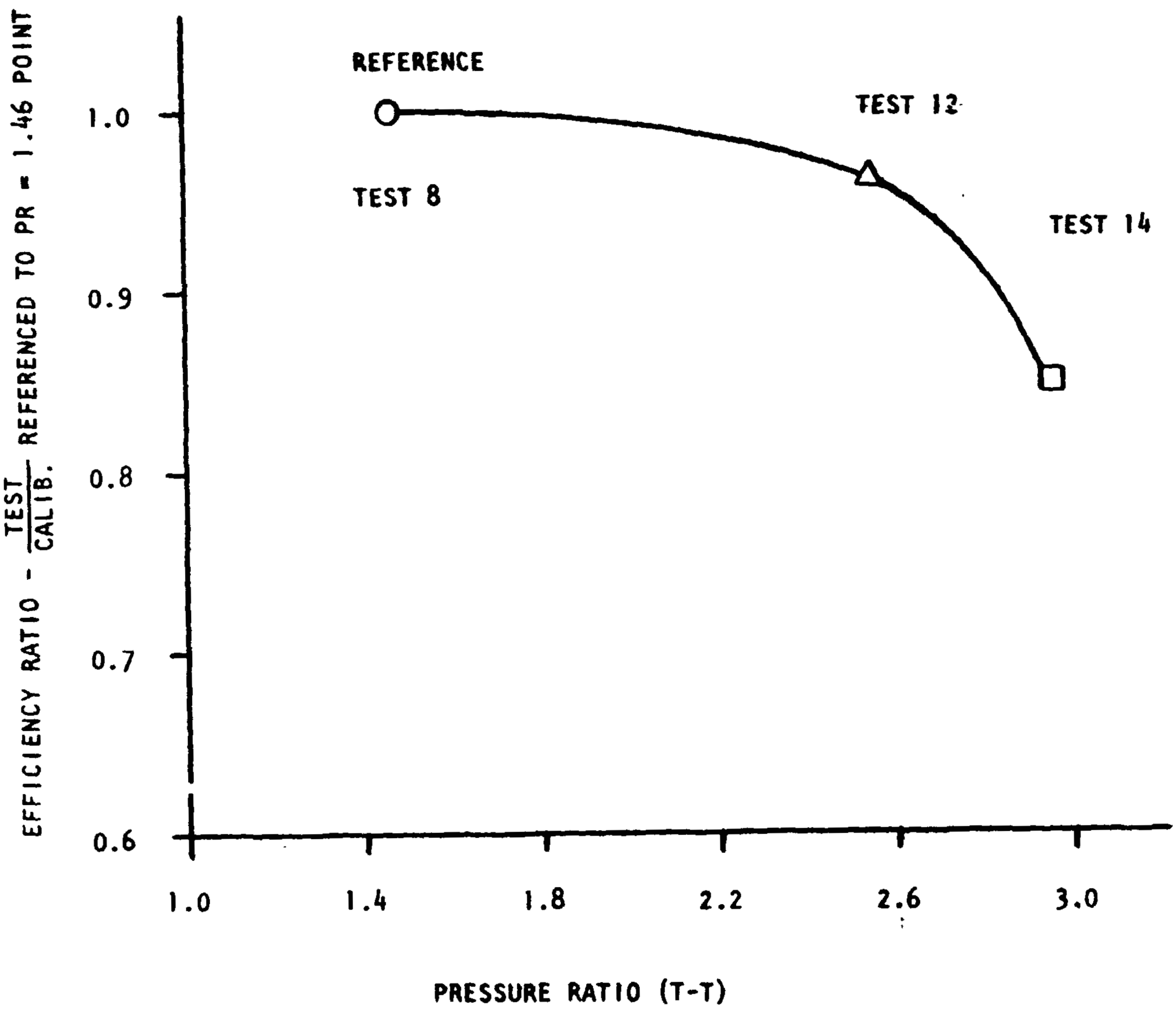

Figure 143. Mark 48-F Turbine, Indicated Effect of Pressure Ratio

by a greater amount at higher pressure rati . The effect of increasing pressure ratio on efficiency could not be established accurately because of the tip seal damage.

Turbine first-stage nozzle outlet cavity pressure was measured and ratioed with turbine inlet pressure and outlet pressure and plotted versus overall turbine pressure ratio in Fig. 144. The ratio of turbine inlet pressure to the first-stage nozzle outlet pressure represents an approximation of first-stage loading. The ratio of the first-stage nozzle outlet pressure to the turbine outlet pressure represents an approximation of second-stage loading since the second nozzle outlet area is smaller than the first and second stage rotor outlet areas. The first-stage loading was limited as overall pressure ratio increased by the small second stage nozzle outlet area designed for low-pressure ratio operation. The plot indicates increased second-stage loading and turbine axial thrust with increased overall pressure ratio.

A flow parameter map calculated from the turbine off-design computer program was established for total-to-total pressure ratios from 1.3 to 2.2, which is the highest pressure ratio obtainable from the program. The turbine flow parameter data from tests 008, 012, and 014 were compared with the flow parameter map shown in Fig. 145. Excellent agreement is shown for the test values with the map. The flow parameter characteristic for an overall pressure ratio of 2.2 is shown to represent the flow parameter data up to a pressure ratio of 3.0.

A conformance ratio was calculated which is defined as the test flow parameter (f_{w1}) tests, divided by the calculated f_{w1} map determined at the test speed parameter and pressure ratio. The data are plotted as a function of pressure ratio as shown in Fig. 146. Good agreement is shown for the large range of speeds and pressure ratios shown.

Turbopump Performance - Pump

The pump performance was analyzed for the hybrid bearing test to verify that the performance was not impaired with the use of hydrostatic bearings. The first consideration was the effect of the hydrostatic bearing on pump head. In test 008, the hydrostatic bearing flow was supplied from an external source. On the pump-end bearing, most of this flow is drained overboard and does not effect the impeller through flow. On the turbine-end; however, the major portion of the hydrostatic bearing flow returns to the second-stage impeller inlet, and adds to the net flow in the second- and third-stage impellers, and is measured as the volumetric flow in the pump discharge venturi. Due to the lower flow through the first impeller stage, (thus developing higher pressure rise) it would be expected that the overall head for the pump on test 008 would be slightly higher than on previous test data. This is the case as is shown in Fig. 147. Similarly, as the internal flow tests 012 and 014 were run, the first-stage impeller supplies the pump-end hydrostatic bearing, then drops overboard. The turbine-end hydrostatic bearing flow is tapped off the pump discharge line before it is measured and routed to the hydrostatic bearings. In all cases, the impeller flow is greater than the measured values by the hydrostatic bearing flow. If the scaled flowrate is adjusted for the hydrostaticstatic bearing flow by approximately 10%, the data of test 012 and 014 matches fairly well with the test data of previous turbopump tests with conventional bearings (Ref. 1).

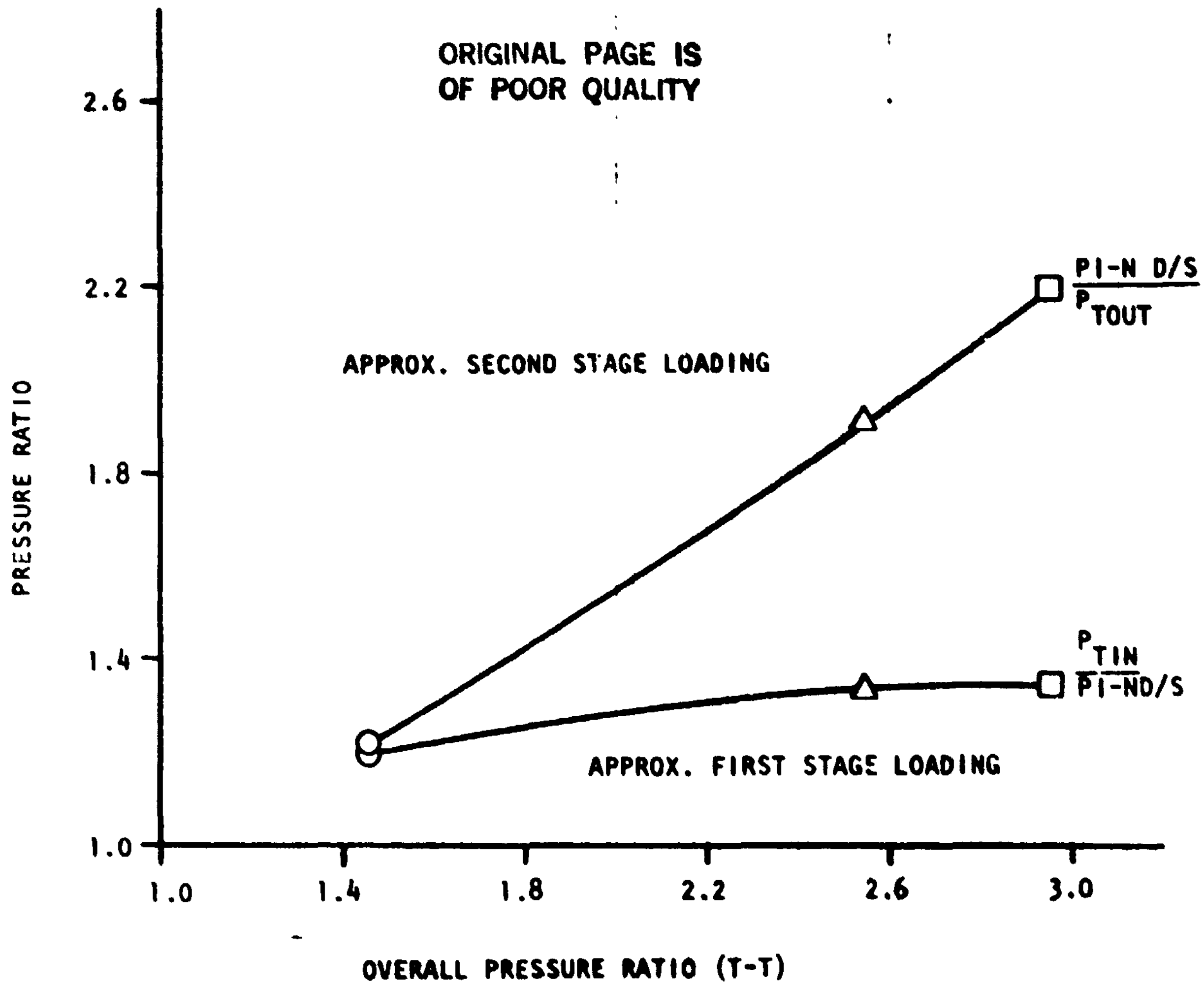

Figure 144. Mark 48-F Turbine, First-Stage Nozzle Outlet Pressure Characteristics

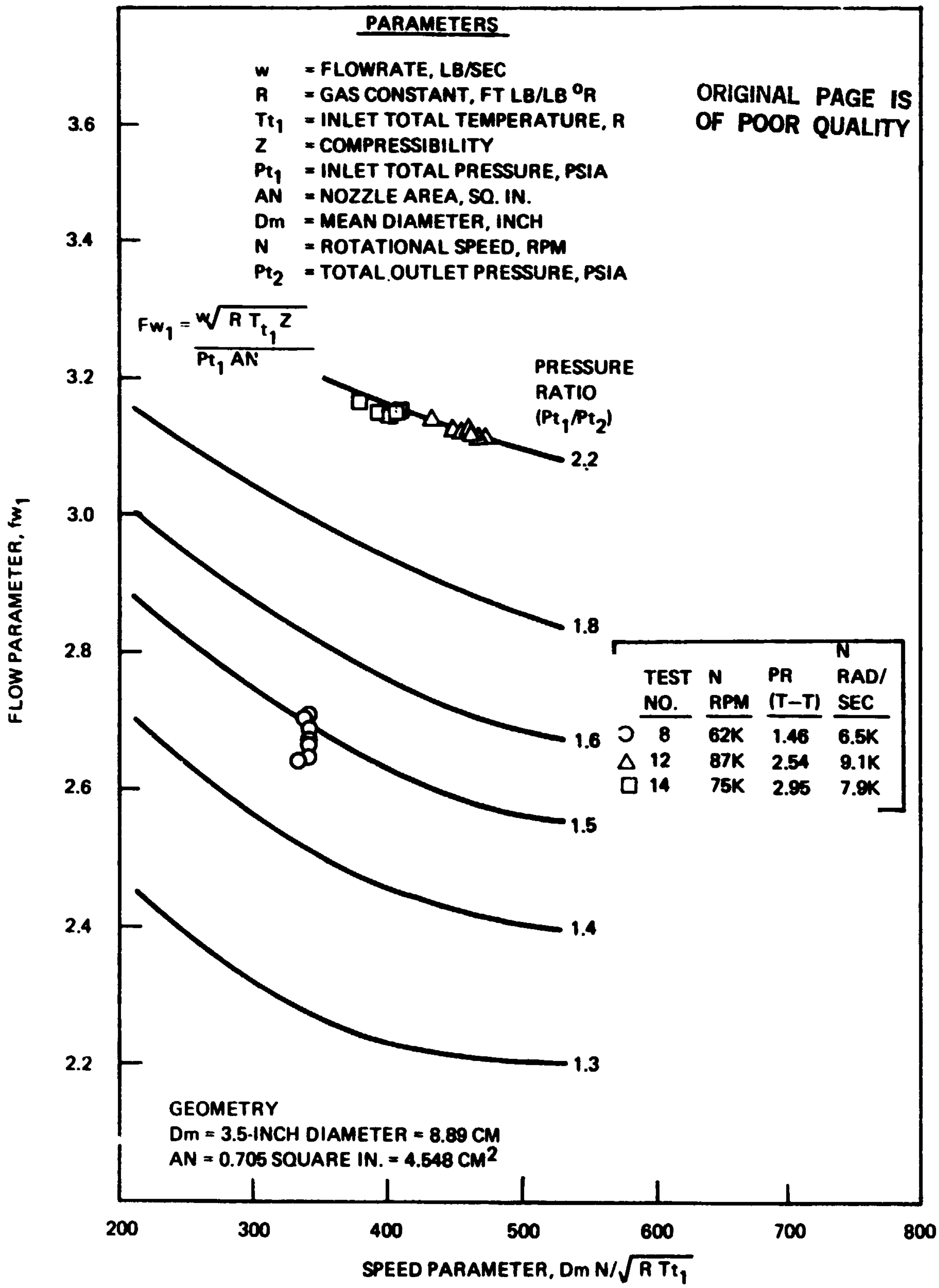

Figure 145. Mark 48-F HPFTP Turbine, Hybrid Bearing Turbopump Tests

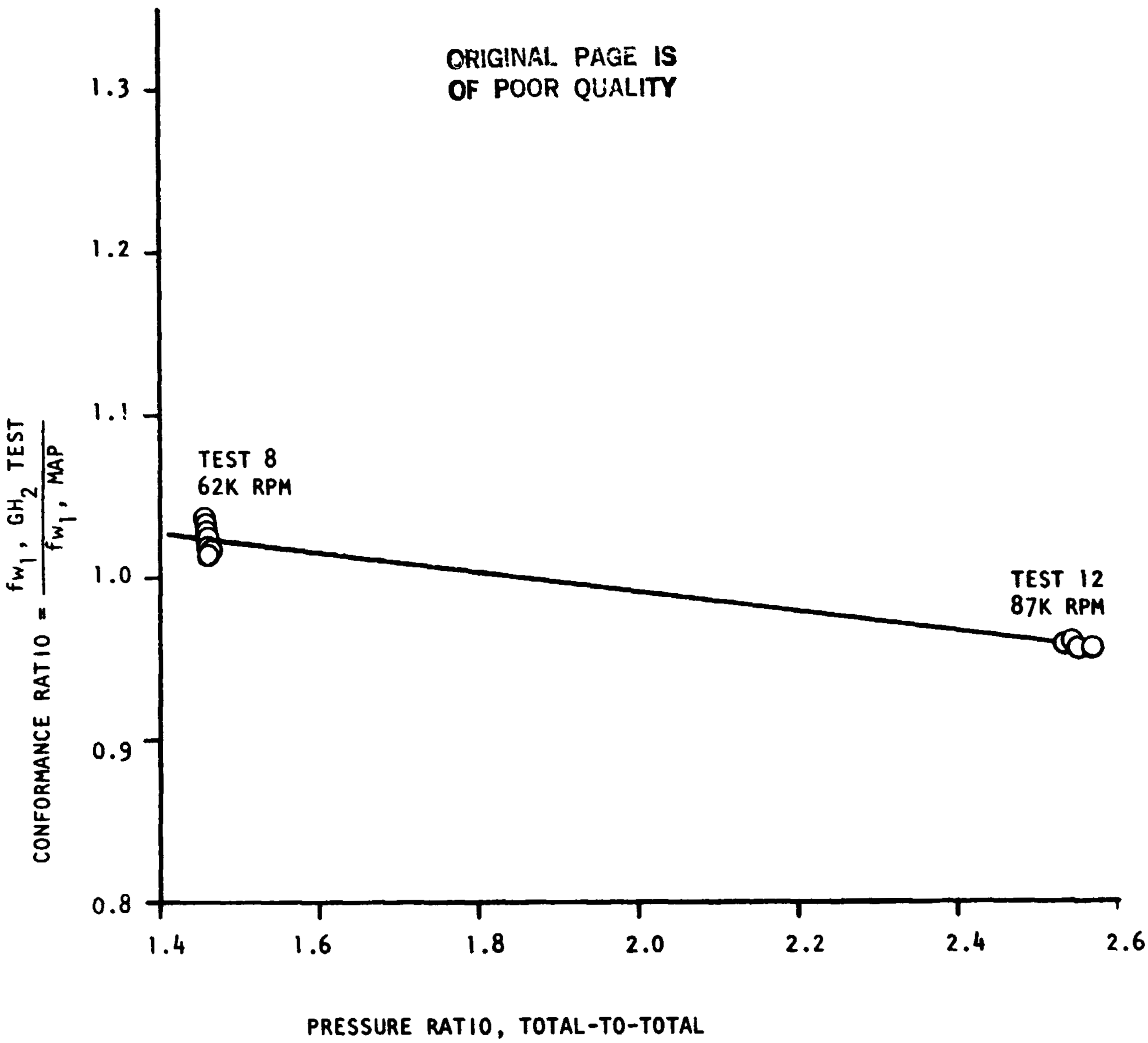

Figure 146. Mark 48-F Turbine Conformance Ratio vs Pressure Ratio

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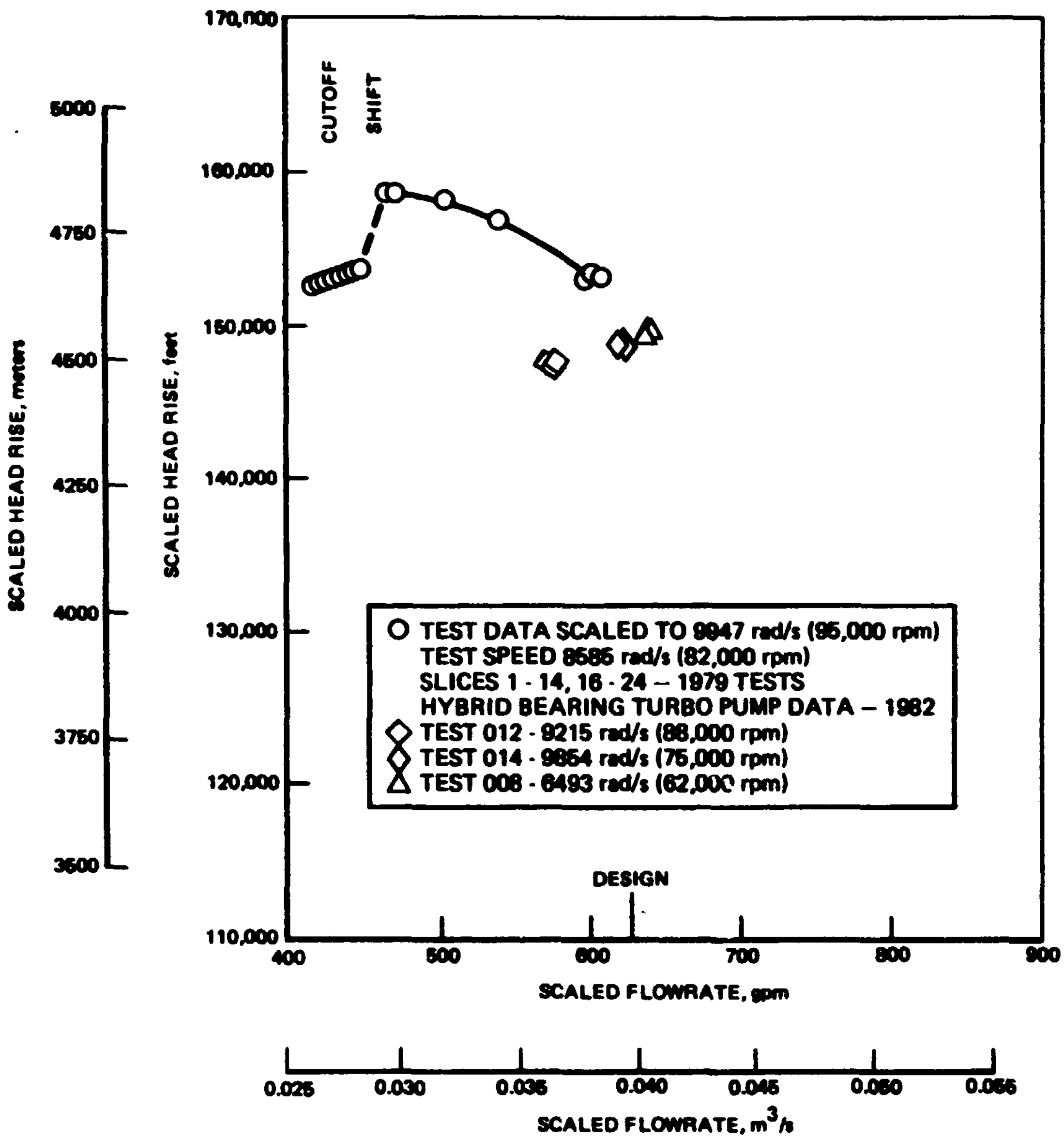

Figure 147. Mark 48-F Pump-Head Flow Performance Comparison

The pump pressure rise of the turbopump is plotted as a function of the discharge flow in Fig. 148. The data for 1979 turbopump tests are given to use as a reference for conventional ball bearings. The hydrostatic bearing data are given for three test speeds. Test 012 data were taken at 8432 to 9320 rad/s (81,000 to 89,000 rpm) and is scaled to 9948 rad/s (95,000 rpm). Test 014 data were taken at 7645 to 8063 rad/s (73,000 to 77,000 rpm) and is scaled to 7854 rad/s (75,000 rpm). The data of test 008 were taken at test speeds near 6493 rad/s (62,000 rpm) and are scaled to 6283 rad/s (60,000 rpm). All the data indicate that the pump head flow performance matches that of the previous turbopump tests data if the effect of the hydrostatic bearing flow is accounted for on tests 012 and 014. It can be concluded from this that the head-flow performance of the turbopump was repeatable between the conventional and hybrid bearing tests if the hydrostatic bearing flow recirculation effect is accounted for. It must be noted, however, that any flow recirculated within the turbopump results in a penalty of efficiency due to the fluid power loss involved.

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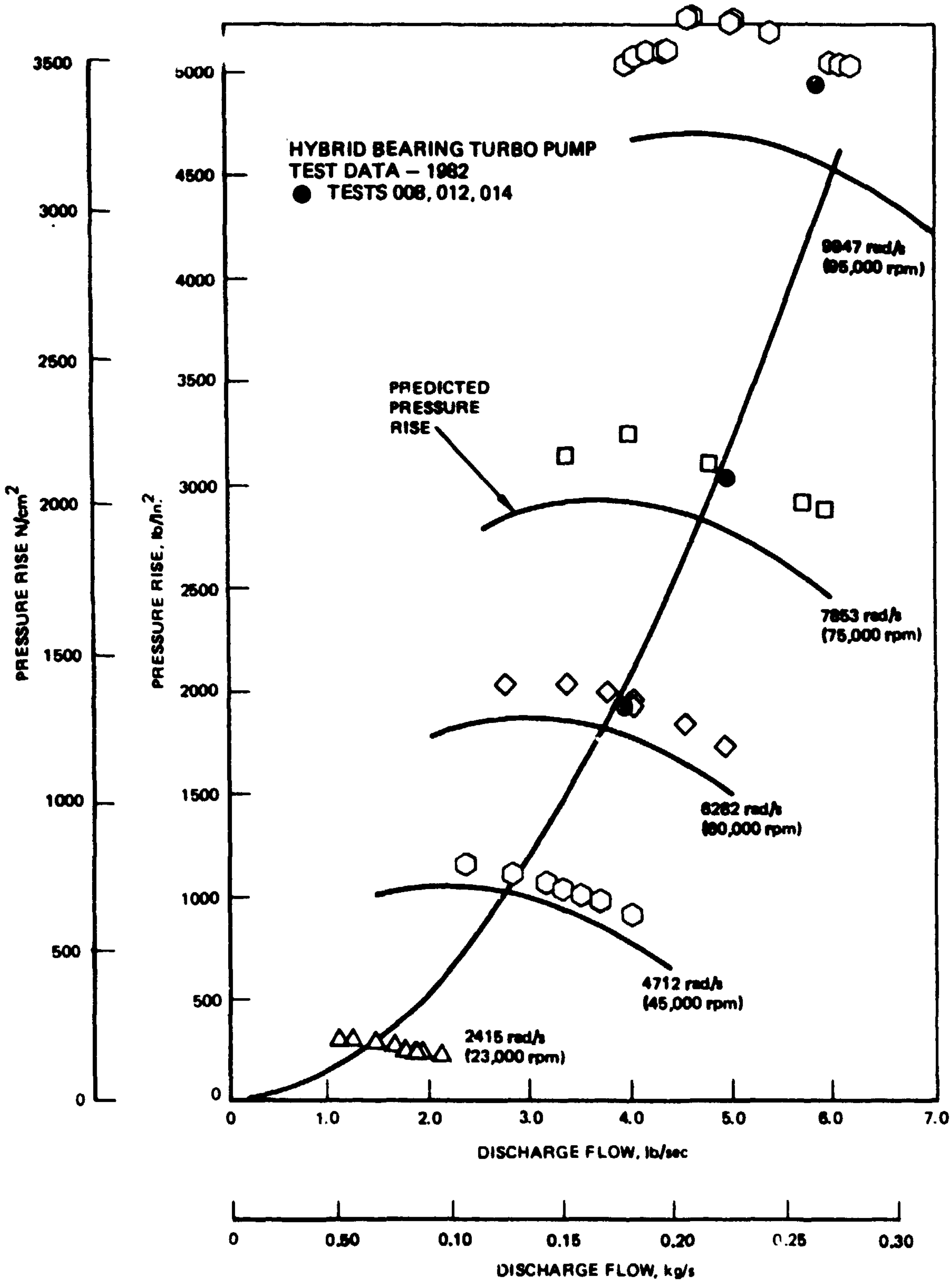

Figure 148. Mark 48-F Pump-Pressure Rise - Flowrate Performance

CONCLUDING REMARKS

The test program and the analysis of the results of the tests of hybrid hydrostatic/ball bearings in a turbopump environment has been very successful. The specific requirements of operation of the hybrid bearing within a turbopump resulted in an enhanced understanding regarding technical applications of these bearings to high-speed turbomachinery. One of the major benefits seen was that operation of the pump-end hybrid bearing to approximately 7330 rad/s (70,000 rpm) was consistently achieved, thus proving the feasibility of hybrid bearing operation. Although the target speed of 9948 rad/s (95,000 rpm) was not achieved, a better understanding as to the speed-limiting barriers that must be overcome further define the advanced technology required for hybrid bearing application. Several major areas that require improved technology are evident from this program. One is the ability to accurately and quickly predict all the direct and cross-coupled stiffness and damping parameters for a given hydrostatic bearing environment. The second is to be able to incorporate all the parameters into an accurate rotodynamic model that can define rotor resonance condition and stability limits for the operating conditions imposed. Another is the design of a turbopump that will have enough axial travel to provide sufficient end-play for the hydrostatic journals or cartridge.

The testing and analysis has led to the following specific conclusions and recommendations:

1. Hybrid hydrostatic/ball bearings are feasible for use in high-speed turbopump application. The tests have shown very satisfactory operation in startup and acceleration as well as in steady-state speeds of up to 7330 rad/s (70,000 rpm). The inability of the hydrostatic bearings to operate above this speed was due to rotodynamic limitations.

2. Hydrostatic bearings pressure and flow internally supplied to the bearings by the pump itself is related to pump shaft speed. As a result, the bearing stiffness and critical speeds increase as the shaft speed increases. If the rotodynamic design is developed properly so that the rotor natural frequency parallels the shaft speed in the operating range without matching it, the critical speed can be avoided and result in a smoothly operating turbopump. Care must be taken, however, in the design of the system. As the shaft speed increases, the bearing direct and cross-coupled stiffness and damping increase as well, but they may also combine to cause the stability limit to reduce with speed increase. If this is the case, it may also require the use of other stabilizing devices such as straight smooth seals independent of the hydrostatic bearing to improve stability at high speed.

3. The proper rotordynamic design of a given turbopump is dependent on the accuracy of prediction of the direct and cross-coupled stiffness and damping coefficients during operation. Also required is the ability to integrate the coupled hybrid bearing (hydrostatic bearing and ball bearing) dynamic coefficients into (and the accuracy of the development of) the rotor dynamics model. The accuracy of predicting the dynamic coefficients has been found lacking as verified by the review of the limited test data. Additional testing, measurement, and analysis of direct and cross-coupled stiffness and damping coefficients in a tester specially designed for this function is required before analytical predictions relating to a turbopump rotor can be trusted.

4. The actual measured values of flowrate were lower than the analytical predictions. The analysis of the test data has resulted in an empirically derived roughness correction parameter, which seems to provide better analytical accuracy. The method accounts for the effective roughness based on the overall pad and bearing configuration. This method should be developed further and verified by further test data as they become available. The turbopump performance data show the performance penalty for using hydrostatic hearings is not great. The inherent speed increase benefit of a hybrid bearing turbopump can also result in improved efficiency and pay back the resultant loss now shown in performance.

5. The test results of the pump-end bearing cartridge data show that it was capable of tracking the shaft speed rotation to approximately 7330 rad/s (70,000 rpm) for the design radial clearances and configuration tested. The rotation of the cartridge was, however, impaired above this speed by high shaft orbiting and housing vibration levels caused by unplanned rotor behavior partly due to the turbine end bearing. It is concluded that cartridge-to-shaft speed matching could occur at even higher shaft speeds than obtained in these tests if rotor orbit levels and casing vibration levels were reduced. The cartridge speed slowdown at higher speeds is caused primarily by cartridge to bearing contact forced by large radial shaft movements and bending modes. This speed threshold also is determined to be a function of radial clearance and the distribution of clearance within the annulus.

6. The results of the assembly, analysis, and tests indicate that the balancing of the rotor during assembly is very critical to the success of the program. This poses a problem in that the number of rotor components requires a procedure to balance several planes during assembly so as not to introduce moment imbalance between the rotor components. In-housing or in-place balancing of the rotor would also be helpful to eliminate the balance changes inherent in the final in-housing assembly process. Another problem occurring with the balance of the hybrid bearing rotor (which includes the ball bearings and cartridges) is the deadband associated with the bearing outer race OD to the cartridge ID. Care must be taken to minimize the deadband and check balance the rotor and cartridges in different positions to minimize the inherent (built-in) imbalance.

7. All the results of the testing of the hybrid hydrostatic bearings indicate that the bearings are extremely rugged and, with solution to the dynamics problems, will provide a very long life. The ball bearings from the turbopump tests were found to be in excellent condition after 14 starts and 1260 seconds of operation. Part of the benefit of the hybrid bearing lies in its inherent "clutch-like" capability to act as a ball-bearing if needed and to act as a hydrostatic bearing when called upon.

8. It is concluded that one of the major inherent design problems associated with the hybrid hydrostatic bearing is the requirement for free end play so as not to interfere with rotation. To ensure end play, it is preferred that the bearing not have responsibility to control the transient axial thrust loads that a balance piston may not be able to control. This problem can be overcome with inclusion of a transient thrust bearing or other transient control methods. If the hybrid bearing is to be responsible for that duty, it is important that there be enough axial forgiveness in the balance piston system to ensure adequate end play margin over the operating life of the turbopump.

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16. Fenwick, J. R., DiJulio, R., Ek, M. C., Ehrgott, R., Green, H., and Shaolian, S.: "Linear Force and Moment Equations for an Annular Smooth Shaft Seal Perturbed Both Angularly and Laterally," Conference on Rotordynamic Instability Problems in High-Performance Turbomachinery, Texas A&M University, 9-11 May 1982.

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NOMENCLATURE

Ar = recess area ratio

Bxx = direct damping coefficient, lb-sec/in.

$\overline{Bxx}$ = dimensionless direct damping coefficient = $\frac{Bxx}{\mu L}\left(\frac{C}{R}\right)^3$

C = clearance, inches

D = journal diameter, inches

FR = friction coefficient

g = gravitational constant = 386.4 in/s^2

G_p = turbulence viscosity correction factor

L = bearing length, inches

L^* = fluid friction length, inches

L_a = axial length from recess to end of bearing, inches

L_c = recess circumferential length, inches

L_p = recess axial width, inches

m = mass flowrate, lb/s

$\bar{\dot{m}}$ = dimensionless mass flowrate = $\frac{\mu\left(\frac{L}{D}\right)\left(1 - \frac{\bar{Y}}{n}\right)\dot{m}}{gG_p \rho c^3 \bar{P}_R (Ps-Pa)}$

n = number of rows of recesses

Ns = shaft speed, rpm

Nc = cartridge speed, rpm

Pa = ambient pressure, psia

Pr = recess pressure, psia

Ps = supply pressure, psia

$\bar{P}_R$ = pressure ratio = $\frac{R_f}{R_f + R_o} = \frac{Pr-Pa}{Ps-Pa}$

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R = journal radius, inches

Ra = axial flow Reynolds No. $= \frac{U_a 2C\rho}{\mu}$

R_e^* = Poiseuille Reynolds number $= \frac{2C^3 \rho (Ps-Pa)\overline{P}_R}{\mu^2 (1 - \frac{\overline{y}}{n}) L}$

R_f = film resistance, $S^2/lb\text{-}in^2$

$\overline{R}_f$ = dimensionless film resistance $= \left[\frac{\rho g G_p C^3 P_R}{\mu (\frac{L}{D}) (1 - \frac{\overline{y}}{n})}\right]^2 (Ps-Pa)\ R_f$

R_o = orifice resistance, $S^2/lb\text{-}in^2$

$\overline{R}_o$ = dimensionless orifice resistance $= \left[\frac{\rho g G_p C^3 \overline{P}_R}{\mu (\frac{L}{D}) (1 - \frac{\overline{y}}{n})}\right]^2 (Ps-Pa)\ R_o$

R_r = rotational Reynolds number $= \frac{U_r C\rho}{\mu}$

T = temperature, R

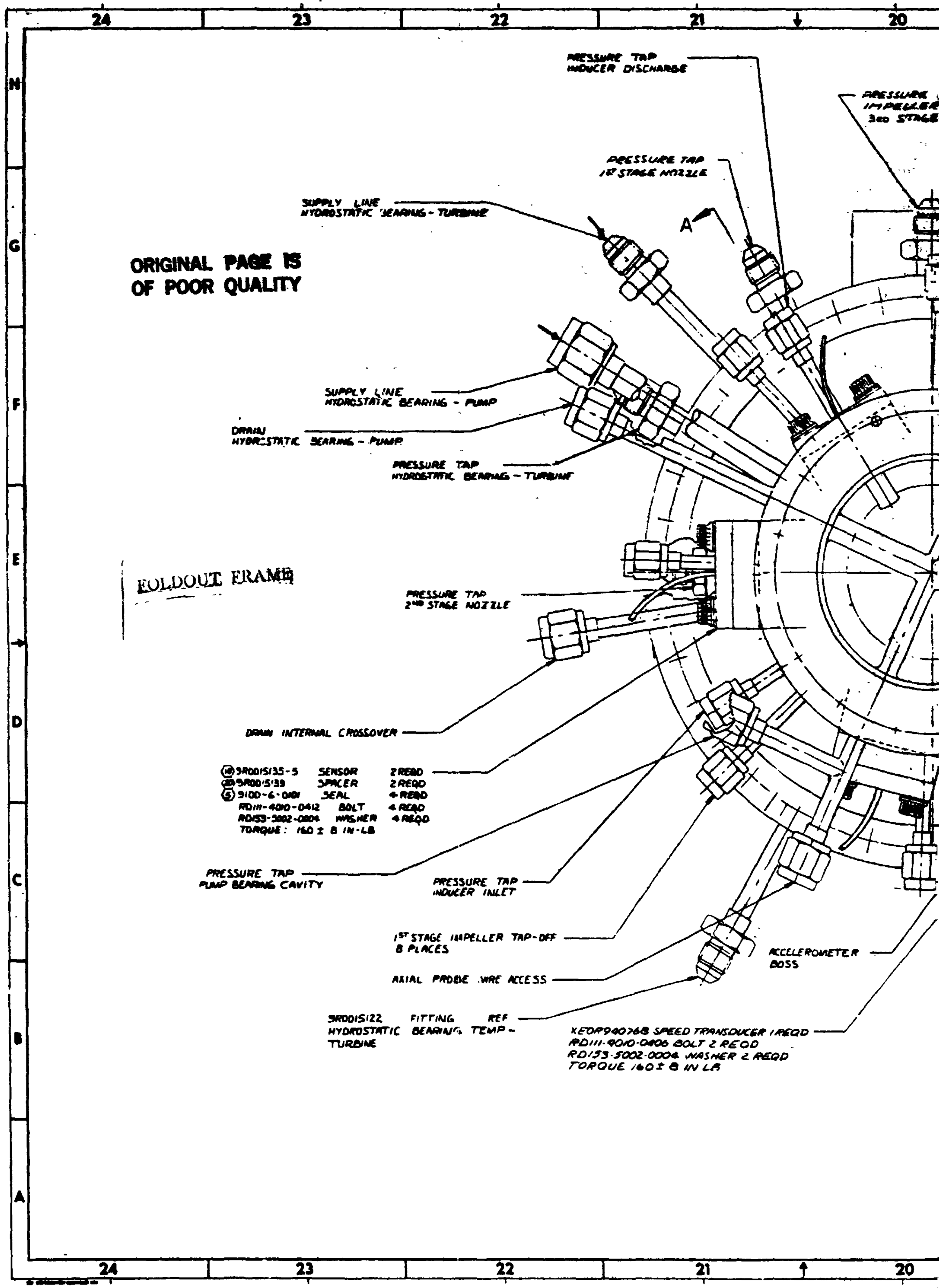
Ua = axial velocity, in./sec

Ur = circumferential velocity, in./sec

x = number of recesses

$\overline{y}$ = recess parameter $= \frac{nL_p}{L}$

Λ = bearing number $= \frac{\mu \omega RL}{G_F C^2 (Ps-Pa)}$



24
23
22
21
20
H
G
F
E
D
C
B
A
PRESSURE TAP
INDUCER DISCHARGE
PRESSURE TAP
1ST STAGE NOZZLE
SUPPLY LINE
HYDROSTATIC BEARING - TURBINE
A
SUPPLY LINE
HYDROSTATIC BEARING - PUMP
DRAIN
HYDROSTATIC BEARING - PUMP
PRESSURE TAP
HYDROSTATIC BEARING - TURBINE
PRESSURE TAP
2ND STAGE NOZZLE
DRAIN INTERNAL CROSSOVER
9R0015135-5 SENSOR 2 REQD
9R0015139 SPACER 2 REQD
9100-6-0101 SEAL 4 REQD
RD111-4010-0412 BOLT 4 REQD
RD153-5002-0004 WASHER 4 REQD
TORQUE: 160 ± 8 IN-LB
PRESSURE TAP
PUMP BEARING CAVITY
PRESSURE TAP
INDUCER INLET
1ST STAGE IMPELLER TAP-OFF
8 PLACES
AXIAL PROBE WIRE ACCESS
ACCELEROMETER
BOSS
9R0015122 FITTING REF
HYDROSTATIC BEARING TEMP - TURBINE
XEOR940768 SPEED TRANSDUCER 1 REQD
RD111-9010-0406 BOLT 2 REQD
RD153-5002-0004 WASHER 2 REQD
TORQUE 160 ± 8 IN LB

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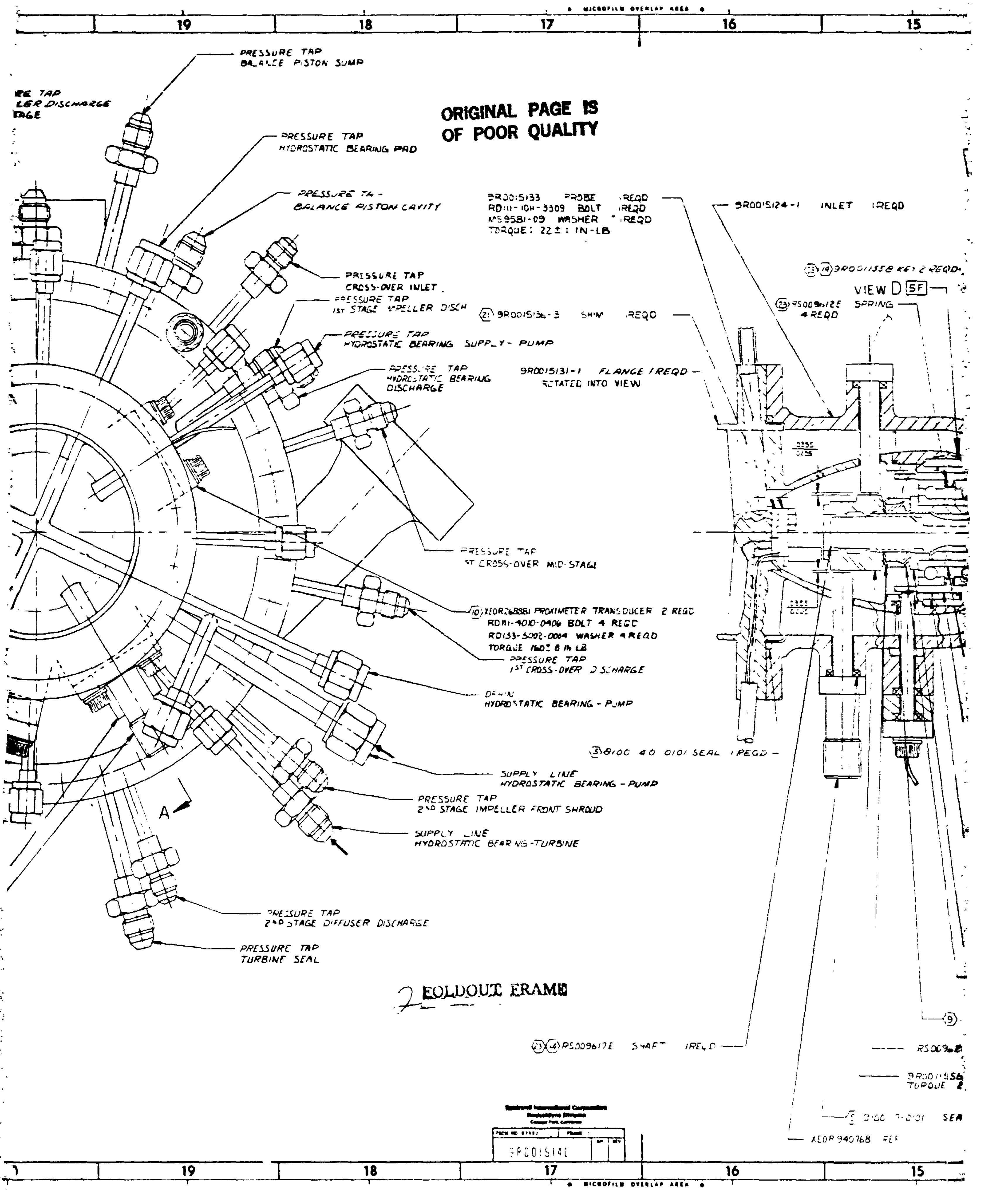
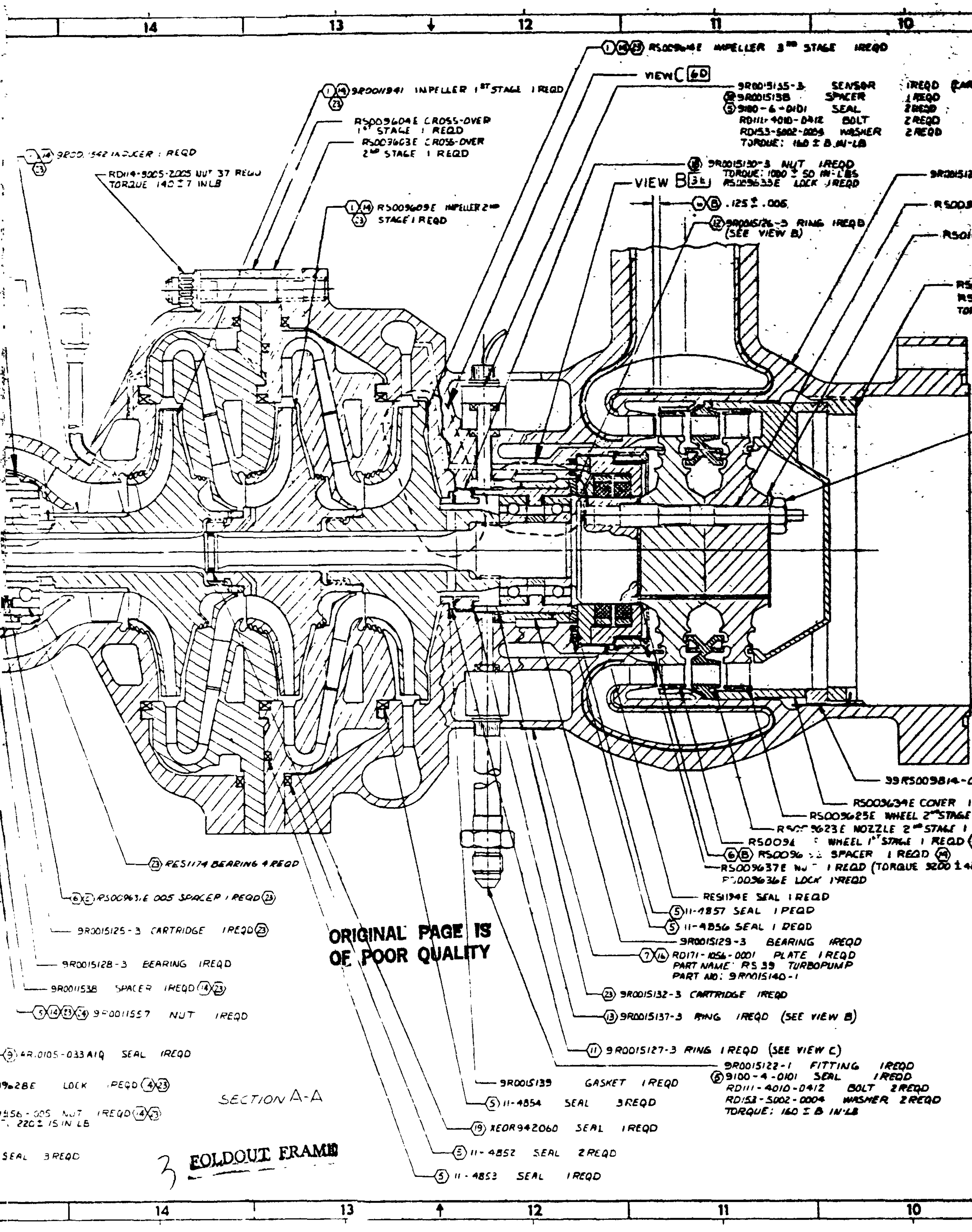


FOLDOUT FRAME

9R0015140



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3 FOLDOUT FRAME

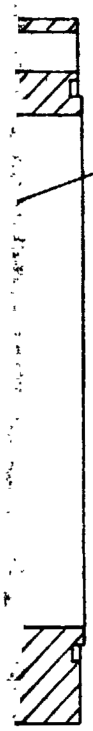
(CARTRIDGE SPEED - TURBINE)

9R0015123-1 HOUSING 1 REQD

R5009635E STUD 3 REQD (14)(23)

R5010137E LOCK 1 REQD (14)(23)

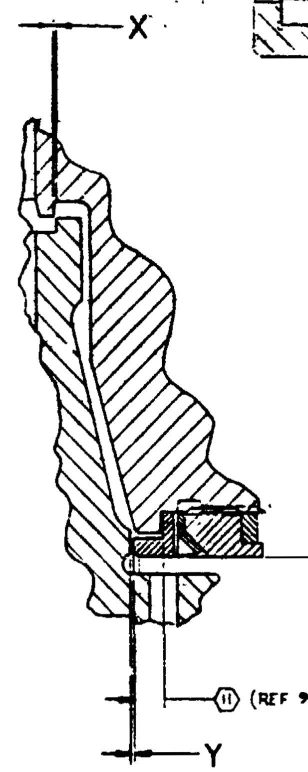
R5009621E NUT 1 REQD
R5005624E LOCK 1 REQD
TORQUE 1400 ± 70 IN LB



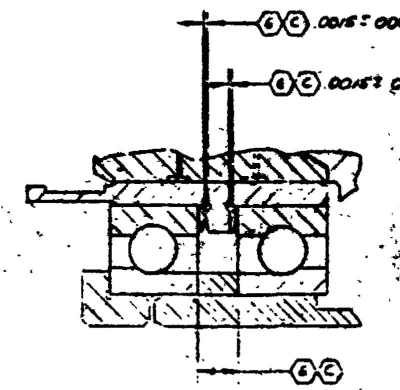
MS9357-10 NUT 3 REQD (23)
TORQUE 60 ± 3 IN LB
STRETCH TO .0085 ± .0008

39814-003 LOCK 1 REQD

NER 1 REQD
STAGE 1 REQD (14)
TAGE 1 REQD
REQD (14)
(14)
1200 ± 460 IN LB)



VIEW C



VIEW D

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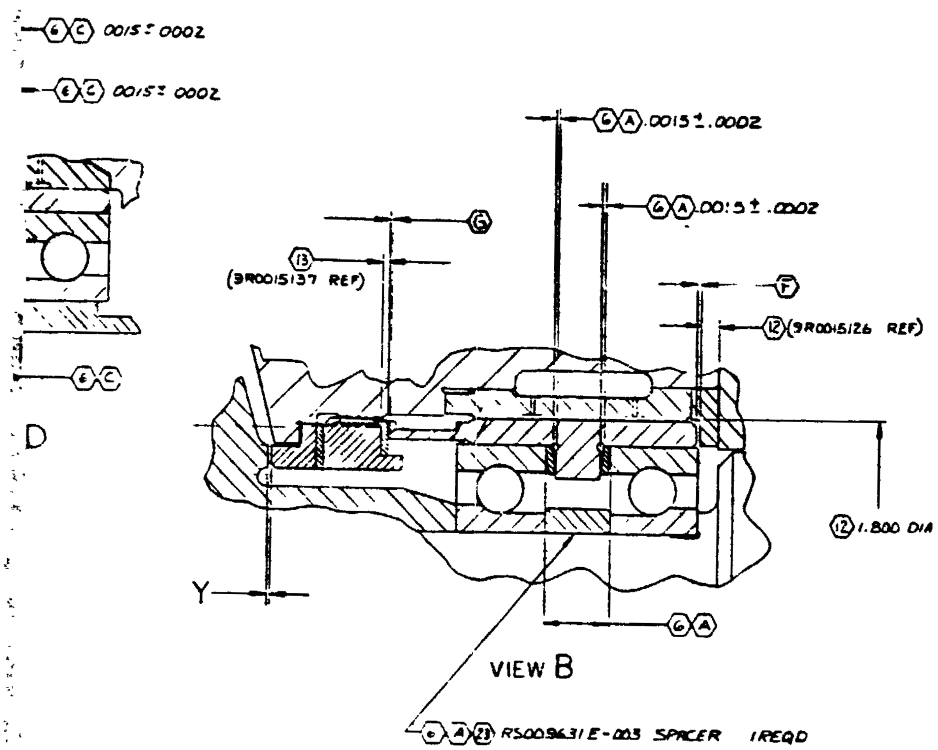
4 FOLDOUT FRAME

(24) MEASURE SHAFT LENGTH. PRELOAD SHAFT IN TENSION TO 7000 ± 500 LBS. TORQUE NUT 300 ± 25 IN-LB. BACK OFF NUT & PRELOAD SHAFT TO 14000 ± 500 LBS TORQUE NUT TO 50 ± 10 IN-LBS. RELEASE SHAFT: RECORD SHAFT STRETCH (.024 = .026 IN)
(23) BALANCE ROTOR ASSY TO WITHIN .02 GRAM INCHES
22 MACHINE PER RA0103-016
(21) MACHINE SHIM TO OBTAIN REQUIRED AXIAL CLEARANCE BETWEEN SENSOR HEAD & FACE OF NUT
(20) MACHINE SPACER PER DETAIL DWG TO OBTAIN REQD GAP BETWEEN SENSOR & CARTRIDGE

9R0015140



APPENDIX A

Hydropump Bearing
Turbopump Assembly
Drawing

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5 FOLDOUT FRAME

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FOR INFORMATION

RING)

19 INSTALL WITH OPEN END TOWARD TURBINE.
18 LUBRICATE WITH MOLYKOTE TYPE Z POWDER PER RA0112-002 METHOD V ON MATING SURFACE OF 9R0015150 & RS009633E.
17 PRIOR TO ASSEMBLY, CLEAN PER RA0110-004, USE MIL-C-81302 ONLY FOR PARTS CODED 1.
16 APPLY PER RA0106-010.
15 SPRAY GS-3 TEFLON LUBT, RAM CHEMICAL INC. GARDENA, CAL. TO 9R0011557 NUT & MATING SURFACES.
14 MATCH MARK ALL ROTOR ASSEMBLY COMPONENTS PER RA0106-008 BY ELECTRO CHEM ETCH. CODED PARTS ARE COMPONENTS OF THE ROTOR ASSEMBLY. ALIGN MATCHMARKS.
13 MACHINE TO OBTAIN A GAP OF ZERO AT G WITH A FORCE OF 400 ± 50 LBS ON THE ROTOR WHEN CLEARANCE AT Y IS .0097 AT LIQUID NITROGEN TEMP PER DETAIL DWG
12 MACHINE TO OBTAIN A GAP OF ZERO AT F WITH A FORCE OF 400 ± 50 LBS ON THE ROTOR WHEN CLEARANCE AT Y IS ZERO AT LIQUID NITROGEN TEMP PER DETAIL DWG
11 MACHINE DIMENSION PER DETAIL DRAWING TO OBTAIN X = 0, WHEN Y = .0042 ± .0002 AT AMBIENT TEMPERATURE.
10 BENTLY-NEVADA CORP. MINDEN, NEVADA.
9 ACCROTRONICS, JACKSON, MICH.
8 INSTALL FITTING AND TUBE ASSEMBLIES PER RA0102-005.
7 IDENTIFY PER RA0104-008.
6 MACHINE SPACER PER DETAIL DRAWING TO OBTAIN MATCH CODED DIMENSIONS.
5 HYDRODYNE DIVISION, F. P. I. INC, NORTH HOLLYWOOD, CA.
4. INSTALL PROTECTIVE COVERS OVER ALL EXPOSED FLANGES, TUBE FITTING & PORTS.
3. LEAK CHECK PUMP ASSEMBLY. ALLOWABLE LEAKAGE RATES:

ALL EXTERNAL FLANGES	ZERO
ALL FITTINGS	ZERO
SHAFT SEAL	150 SCIM MAX He GAS

TEST CONDITIONS FOR LEAK TEST:

UP STREAM	30 ± 1 PSIG
DOWN STREAM	ATMOS
TEMP	AMBIENT

2 INSTALL THREADED FASTENERS PER RA0101-002.
1 TITANIUM PART. CLEAN WITH MIL-C-81302 ONLY.

TENSION IN-LB ± 500 LBS SHAFT: 1)

CLEARANCE

REQD

-1
ASSY NO

SEE SEPARATE PARTS LIST

247

NONE
NONE

TURBOPUMP, HYBRID BEARING · ASSY

J 02602 9R0015140

APPENDIX B

Summary of
Hybrid Bearing
Test Data

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MK48-F

LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 1
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COMMENTS . . .

M-2 HYBRID BEARING TEST. BLOWDOWN TEST.
OVERRODE TURB BRG RPM. TURB IN TOT PR AND TUR IN DS PR WERE SWITCHED.
NO TURB DRIVE GAS.

AMBIENT PRESSURE		13.8000
LO2 VENTURI (GG)		
P/N V160248-SGR	UPSTREAM DIAMETER	0.0
S/N 8871	THROAT DIAMETER	0.0
	THROAT CD	0.0
GH2 VENTURI (TURB)		
P/N VP031200-SGR	UPSTREAM DIAMETER	2.3000
S/N 9731	THROAT DIAMETER	1.3085
	THROAT CD	0.9873
LH2 VENTURI (GG)		
P/N V320471-SGR	UPSTREAM DIAMETER	0.0
S/N 8873	THROAT DIAMETER	0.0
	THROAT CD	0.0
LH2 VENTURI (PUMP DISCH)		
P/N V320709-SGR	UPSTREAM DIAMETER	1.6890
S/N 8874	THROAT DIAMETER	0.7090
	THROAT CD	0.9760

TURBINE SYSTEM EFF. AREA		0.70470
TURBINE EXHAUST ORIFICE	4 EACH	0.31200
	4 EACH	0.32500
	1 EACH	0.30800

HYDROSTATIC BEARING SUPPLY SYSTEM

TURBINE	INLET DUCT DIA	0.334	ORIFICE DIA	0.194
PUMP	INLET DUCT DIA	0.402	ORIFICE DIA	0.175

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

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G A S E O U S   H Y D R O G E N   T U R B I N E   D R I V E   P A R A M E T E R S

TIME SLICE NO	BEGIN TIME (SEC)	END TIME (SEC)	REG U/S PR (PSIA)	VENTURI U/S PR (PSIA)	VENTURI U/S TEMP (DEG R)	VENTURI DELTA PR (PSID)	SPIN VALVE POSN	SPIN VALVE U/S PR (PSIA)	FAC DUCT PR (PSIA)	TURB GH2 FLOW (LB/SEC)	SPEED (RPM)
1	214.966	215.152	4845.8	14.7	527.59	0.00	1.53	14.5	13.80	0.0036	364.
2	215.461	215.647	4845.9	14.5	527.60	0.00	1.55	15.0	13.80	0.0043	365.
3	215.997	216.142	4845.7	14.4	527.60	0.00	1.53	14.8	13.77	0.0028	367.
4	216.492	216.637	4846.1	14.8	527.60	0.00	1.55	14.7	13.79	0.0040	364.
5	216.987	217.131	4846.1	14.8	527.60	0.00	1.54	14.7	13.77	0.0040	366.
6	217.482	217.676	4846.1	14.9	527.62	0.00	1.53	14.5	13.81	0.0040	373.
7	217.977	218.121	4845.1	14.4	527.63	0.0	1.53	15.2	13.82	0.0000	377.
8	218.472	218.657	4844.7	14.5	527.61	0.00	1.52	14.4	13.76	0.0035	387.
9	218.967	219.152	4842.5	14.7	527.60	0.00	1.54	15.0	13.77	0.0044	391.
10	219.462	219.647	4841.3	14.5	527.61	0.00	1.53	15.3	13.80	0.0035	346.
11	219.998	220.142	4837.3	14.4	527.62	0.0	1.53	14.7	13.77	0.0000	280.
12	220.493	220.637	4836.1	14.4	527.60	0.00	1.50	14.7	13.76	0.0039	215.
13	220.988	221.132	4833.7	14.8	527.60	0.00	1.52	14.7	13.81	0.0049	153.
14	221.483	221.627	4831.0	14.8	527.60	0.00	1.51	14.7	13.81	0.0028	56.
15	221.978	222.122	4828.6	14.6	527.63	0.00	1.50	14.5	13.77	0.0049	21.
16	222.473	222.658	4825.4	14.0	527.62	0.0	1.47	14.9	13.77	0.0000	9.
17	222.968	223.153	4822.9	14.4	527.61	0.00	1.47	14.6	13.78	0.0035	4.
18	223.462	223.648	4820.2	14.7	527.61	0.00	1.47	14.9	13.80	0.0044	2.
19	223.999	224.143	4816.8	14.8	527.60	0.0	1.45	14.8	13.81	0.0000	1.
20	224.494	224.638	4814.4	14.4	527.60	0.00	1.45	14.8	13.71	0.0039	1.
21	224.989	225.133	4811.0	14.8	527.61	0.00	1.47	14.8	13.77	0.0040	1.
22	225.483	225.628	4808.2	14.8	527.60	0.0	1.44	14.7	13.79	0.0000	1.
23	225.979	226.123	4804.8	14.4	527.61	0.00	1.48	14.7	13.77	0.0028	1.
24	226.473	226.659	4801.4	14.7	527.60	0.00	1.46	14.9	13.76	0.0025	0.
25	226.968	227.154	4798.5	14.4	527.61	0.00	1.46	14.4	13.76	0.0035	0.

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

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H Y B R I D B E A R I N G D A T A
PUMP - END (PAGE 1)

TIME SLICE NO	PUMP BRG SUPPLY U/S PRESS (PSIA)	PUMP BRG SUPPLY TEMP (DEG R)	PUMP BRG SUPPLY D/S ORIF PRESS (PSIA)	PUMP BRG SUPPLY ORIF DP (PSID)	PUMP BRG SUPPLY MANIF PRESS (PSIA)	--- PUMP BRG PAD PRESSURES --- 3.00 OCLOCK (PSIA)	9.00 OCLOCK (PSIA)	6.30 OCLOCK (PSIA)
1	131.9	90.7	169.9	4.4	143.8	111.6	114.2	2.9
2	131.5	90.8	169.9	4.3	143.8	112.2	114.6	2.8
3	131.1	90.8	169.9	4.2	143.3	112.5	114.5	2.8
4	130.6	90.8	169.9	4.1	142.9	112.9	115.1	3.0
5	130.1	90.8	169.9	3.9	142.5	112.9	115.1	3.0
6	129.6	90.8	169.9	3.8	142.1	113.4	115.4	3.0
7	129.6	90.8	169.9	3.7	141.7	113.5	115.3	3.1
8	128.5	90.8	169.9	3.5	141.0	113.6	116.2	2.9
9	144.8	91.3	182.4	6.1	154.8	114.9	117.9	2.9
10	292.7	93.4	328.1	18.5	289.8	132.4	131.5	2.9
11	427.7	95.0	483.2	25.4	416.1	161.1	158.9	3.1
12	539.7	96.5	561.5	31.0	521.3	195.3	193.1	2.8
13	640.1	97.4	639.8	35.6	616.5	230.7	226.8	2.9
14	710.6	97.4	718.1	38.9	683.3	253.3	249.1	3.7
15	720.2	93.0	718.1	38.4	693.4	257.6	251.4	4.4
16	639.6	87.3	644.5	32.3	621.7	232.7	226.7	5.0
17	490.6	82.4	495.7	24.8	481.8	183.1	179.1	4.6
18	392.3	79.3	412.7	20.3	388.9	155.2	152.0	4.0
19	326.2	77.5	336.3	17.2	325.9	139.6	137.0	3.9
20	284.3	76.6	326.5	15.3	286.7	130.5	128.5	3.4
21	256.8	75.8	326.5	14.1	260.0	123.3	121.4	3.6
22	233.0	75.3	248.2	13.0	237.7	109.2	107.4	3.6
23	213.4	75.0	248.2	12.3	218.5	100.0	98.3	3.5
24	198.8	74.9	248.2	11.5	204.3	93.7	92.5	3.4
25	187.0	74.9	248.2	10.9	193.2	88.1	86.7	3.5

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HYBRID BEARING DATA
PUMP - END (PAGE 2)

TIME SLICE NO	PUMP BRG SUMP PRESSURE (PSIA)	PUMP BRG SUMP OUT PRESSURE (PSIA)	PUMP BRG SUMP OUT TEMP (DEG R)	SHAFT SPEED (RPM)	CARTRIDGE SPEED (RPM)	PUMP BRG FLOW (LB/SEC)	LH2 DENSITY AT ORIF (PCF)	AVERAGE PAD PRESSURE (PSIA)	PUMP BRG PRESSURE RATIO
1	109.1	63.7	47.2	366.	368.	0.0128	0.2944	112.9	0.1089
2	109.5	63.7	47.2	365.	366.	0.0127	0.2933	113.4	0.1127
3	109.7	63.9	47.2	367.	366.	0.0125	0.2923	113.5	0.1138
4	110.1	63.6	47.2	366.	367.	0.0124	0.2910	114.0	0.1188
5	110.3	63.8	47.2	366.	367.	0.0120	0.2898	114.0	0.1165
6	110.6	63.5	47.1	373.	370.	0.0118	0.2886	114.4	0.1205
7	110.9	63.2	47.0	377.	374.	0.0116	0.2886	114.4	0.1147
8	111.2	63.1	46.9	397.	380.	0.0113	0.2860	114.9	0.1248
9	111.8	64.0	46.9	391.	387.	0.0158	0.3230	116.4	0.1073
10	113.8	56.8	46.2	346.	371.	0.0401	0.6860	132.0	0.1030
11	113.1	51.9	47.3	280.	324.	0.0578	1.0372	160.0	0.1547
12	115.4	52.4	53.2	215.	266.	0.0721	1.3221	194.2	0.1942
13	115.0	45.8	100.5	153.	153.	0.0843	1.5714	228.7	0.2269
14	115.2	46.6	112.2	56.	56.	0.0931	1.7564	251.2	0.2394
15	113.3	47.5	115.3	71.	71.	0.0976	1.9529	254.5	0.2434
16	113.7	48.8	114.1	9.	9.	0.0903	1.9830	229.7	0.2284
17	112.5	49.5	110.9	4.	4.	0.0731	1.6939	181.1	0.1958
18	111.6	49.9	108.3	2.	2.	0.0601	1.4025	153.6	0.1514
19	111.2	50.3	105.5	1.	1.	0.0500	1.1477	138.3	0.1263
20	109.0	50.1	101.8	1.	1.	0.0434	0.9713	129.5	0.1152
21	106.5	59.2	66.7	1.	1.	0.0392	0.8627	122.3	0.1029
22	92.3	50.0	49.4	1.	1.	0.0356	0.7663	108.3	0.1102
23	84.1	44.5	46.5	1.	1.	0.0327	0.6862	99.1	0.1118
24	79.6	41.9	49.4	0.	0.	0.0302	0.6275	93.1	0.1150
25	73.3	39.7	49.2	0.	0.	0.0284	0.5913	87.4	0.1178

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H Y B R I D B E A R I N G D A T A
PUMP - END (PAGE 3)

TIME SLICE NO	BRG DELTA P ORIFICE PSID	BRG DELTA P FILM PSID	BRG DELTA P TOTAL PSID	ORIFICE RESISTANCE SEC**2/ LB-IN**2	FLUID FILM RESISTANCE SEC**2/ LB-IN**2	POISEUILLE RENOLDS NO	COUETTE RENOLDS NO	LAMBDA BRG NO	TORQUE FLUID FILM (TEMP) IN-LBS
1	31.0	3.8	34.7	190084.0	23237.5	4372629.	80.	0.00008	-852.8660
2	30.4	3.9	34.3	190117.4	24140.7	4333257.	80.	0.00008	-850.5279
3	29.8	3.8	33.6	190671.5	24482.1	4247551.	80.	0.00008	-841.5826
4	28.9	3.9	32.8	188811.7	25453.8	4155285.	80.	0.00008	-832.1028
5	28.5	3.8	32.3	198687.4	26198.2	4096316.	80.	0.00008	-803.4326
6	27.7	3.8	31.5	200245.8	27426.8	4008629.	81.	0.00008	-784.7574
7	27.2	3.5	30.8	201529.7	26109.3	3920294.	82.	0.00008	-763.0555
8	26.1	3.7	29.8	203880.7	29072.4	3813959.	84.	0.00008	-736.5142
9	38.3	4.6	43.0	153007.6	18388.2	5459218.	85.	0.00008	-1010.7160
10	157.8	18.1	176.0	98189.2	11275.1	22521420.	84.	0.00004	-2535.0649
11	256.1	46.9	302.9	76656.4	14026.0	40534677.	79.	0.00002	-1116.6508
12	327.1	78.8	405.9	62933.1	15171.0	58050816.	71.	0.00002	-1117.2075
13	387.7	113.8	501.5	54581.6	16016.1	76056731.	44.	0.00001	4360.8494
14	432.1	136.0	568.1	49862.1	15693.6	90476902.	17.	0.00000	18986.3594
15	438.9	141.2	580.1	46108.7	14832.5	103383827.	7.	0.00000	64020.7613
16	392.0	116.0	508.0	48118.0	14243.5	100636044.	3.	0.00000	**********
17	300.7	68.6	369.3	56780.7	12844.6	75106549.	2.	0.00000	**********
18	235.3	42.0	277.3	65167.6	11630.7	58280692.	1.	0.00000	**********
19	187.6	27.1	214.7	75065.7	10852.0	45821057.	0.	0.00000	**********
20	157.2	20.5	177.7	83378.5	9859.0	37667204.	0.	0.00000	**********
21	137.7	15.8	153.5	89432.0	10260.2	32237580.	0.	0.00000	**********
22	129.4	16.0	145.4	102245.0	12641.0	27328438.	0.	0.00000	**********
23	119.3	15.0	134.4	111786.9	14063.9	23330827.	0.	0.00000	**********
24	111.3	14.5	125.7	121865.3	15828.4	20565546.	0.	0.00000	**********
25	105.8	14.1	120.0	131475.9	17551.6	18422150.	0.	0.00000	**********

ORIGINAL PAGE IS
OF POOR QUALITY

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 1
TEST DATE 5-25-82

PROCESSING DATE 5-27-82
TEST DURATION, SEC 262.00

H Y B R I D   B E A R I N G   D A T A
PUMP AND TURBINE END (PAGE 4)

	- - - PUMP - - -			- - - TURBINE - - -					
TIME SLICE NO	HS BRG CLEARANCE RADIAL IN	VISCOSITY PUMP BRG LB-HR/FT**2 * E10	CSUBP PUMP BRG BTU/ LB-R	HS BRG CLEARANCE RADIAL IN	VISCOSITY TURB BRG LB-HR/FT**2 * E10	CSUBP TURB BRG BTU/ LB-R	POISEUILLE RENOLDS NO	COUETTE RENOLDS NO	LAMBDA TURB NO
1	0.00246	0.15170	2.7828	0.00246	0.20923	2.8967	971293.	0.	0.0000
2	0.00246	0.15176	2.7842	0.00246	0.20917	2.8959	940389.	0.	0.0000
3	0.00246	0.15181	2.7843	0.00246	0.20913	2.8950	906759.	0.	0.0000
4	0.00246	0.15185	2.7857	0.00246	0.20903	2.8933	865156.	0.	0.0000
5	0.00246	0.15185	2.7858	0.00246	0.20896	2.8920	834046.	0.	0.0000
6	0.00246	0.15188	2.7868	0.00246	0.20893	2.8913	775908.	0.	0.0000
7	0.00246	0.15188	2.7870	0.00246	0.20890	2.8904	753235.	0.	0.0000
8	0.00246	0.15191	2.7884	0.00246	0.20884	2.8887	665341.	0.	0.0000
9	0.00246	0.15261	2.7893	0.00246	0.20997	2.9097	1299665.	0.	0.0000
10	0.00246	0.15404	2.8197	0.00246	0.21505	3.0453	9308348.	0.	0.0000
11	0.00246	0.15977	2.8868	0.00246	0.21882	3.1555	20360868.	0.	0.0000
12	0.00246	0.16374	2.9705	0.00246	0.22332	3.2486	31835799.	0.	0.0000
13	0.00246	0.16724	3.0597	0.00246	0.22751	3.3276	44574313.	0.	0.0000
14	0.00246	0.16896	3.1277	0.00246	0.23012	3.3887	58203924.	0.	0.0000
15	0.00246	0.16498	3.2347	0.00246	0.22589	3.4359	80215378.	0.	0.0000
16	0.00246	0.15717	3.2950	0.00246	0.21806	3.4824	97944733.	0.	0.0000
17	0.00246	0.14789	3.2003	0.00246	0.20672	3.4547	83872440.	0.	0.0000
18	0.00246	0.14118	3.1370	0.00246	0.19862	3.4226	71956063.	0.	0.0000
19	0.00246	0.13751	3.0942	0.00246	0.19367	3.3616	59463532.	0.	0.0000
20	0.00246	0.13565	3.0639	0.00246	0.18971	3.3137	51072698.	0.	0.0000
21	0.00246	0.13408	3.0387	0.00246	0.18760	3.2456	42126384.	0.	0.0000
22	0.00246	0.13225	2.9623	0.00246	0.18575	3.1850	35781476.	0.	0.0000
23	0.00246	0.13111	2.9124	0.00246	0.18449	3.1282	30177295.	0.	0.0000
24	0.00246	0.13044	2.8793	0.00246	0.18329	3.0720	25874678.	0.	0.0000
25	0.00246	0.12990	2.8483	0.00246	0.18276	3.0471	22467019.	0.	0.0000

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RUN NUMBER 1
TEST DATE 5-25-82

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H Y B R I D B E A P I N G D A T A
TURBINE END (PAGE 1)

TIME SLICE NO	TURB BRG SUPPLY U/S PRESS (PSIA)	TURB BRG SUPPLY U/S TEMP (DEG R)	TURB BRG SUPPLY D/S ORIF PRESS (PSIA)	TURB BRG SUPPLY ORIF DP (PSID)	TURB BRG SUPPLY MANIF PRESS (PSIA)	TURB BRG DISCH PRESS (PSIA)	TURB BRG SUMP PRESS (PSIA)	— TURBINE BRG — DISCHARGE LINE PRESS (PSIA)	— TURBINE BRG — DISCHARGE LINE TEMP (DEG R)
1	131.2	141.5	129.2	0.0	129.8	117.6	104.6	45.8	44.8
2	131.2	141.4	129.0	0.0	129.4	117.5	105.0	45.9	44.8
3	130.9	141.4	128.7	0.0	128.6	117.4	105.1	46.0	44.8
4	130.1	141.3	128.0	0.0	127.4	117.5	105.4	45.9	44.8
5	129.2	141.3	127.0	0.0	126.6	117.5	105.6	46.2	44.8
6	128.7	141.3	126.5	0.0	126.0	117.5	105.8	46.4	44.8
7	126.9	141.2	126.3	0.0	125.2	117.7	106.0	46.5	44.8
8	126.5	141.2	124.7	0.0	123.6	117.8	106.1	46.6	44.8
9	145.2	141.9	141.9	0.0	139.9	119.7	107.7	49.2	45.2
10	292.4	144.4	282.8	0.0	270.8	126.5	112.2	34.5	89.7
11	425.2	145.9	411.2	0.0	389.9	130.9	115.4	35.0	115.9
12	540.1	148.2	522.6	0.4	494.6	140.9	124.0	37.1	122.2
13	650.7	150.1	629.7	3.5	595.1	[illegible]	130.1	38.3	125.7
14	750.4	150.6	725.5	7.4	685.5	155.0	136.5	39.3	127.7
15	840.7	143.7	811.3	11.9	766.6	161.4	141.6	41.0	125.8
16	857.6	133.9	828.4	12.2	783.0	164.2	144.4	43.0	118.7
17	728.6	125.4	704.4	7.0	665.8	153.0	134.5	42.5	112.2
18	635.4	120.0	613.8	3.4	581.1	145.4	127.9	42.0	108.0
19	558.5	117.5	540.0	0.0	512.0	138.9	122.7	41.2	105.9
20	504.6	115.3	487.7	0.0	462.6	133.8	118.1	40.2	104.9
21	455.1	114.6	438.7	0.0	416.7	128.3	113.2	39.2	104.7
22	413.1	114.2	398.7	0.0	379.0	113.5	99.2	36.2	105.2
23	377.4	114.0	363.9	0.0	346.1	104.4	90.3	34.6	105.9
24	346.5	113.8	333.9	0.0	318.7	97.9	84.1	33.3	106.6
25	321.8	114.0	310.1	0.0	296.8	91.8	78.3	32.2	107.4

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RUN NUMBER 1
TEST DATE 5-25-82

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TEST DURATION, SEC 262.00

H Y B R I D   B E A R I N G   D A T A
TURBINE END (PAGE 2)

TIME SLICE NO	SHAFT SPEED (RPM)	TURBINE CARTRIDGE SPEED (RPM)	TURBINE H/S BRG FLOW (LB/SEC)	LH2 DENSITY AT ORIF (PCF)	TURB BRG SUPPLY MANIF PRESS (PSIA)	TURB BRG DISCH PRESS (PSIA)	TURB BRG SUMP PRESS (PSIA)	HYDROSTATIC BEARING DELTA PRESS (PSID)
1	364.	1.	0.0	0.177	129.8	117.6	104.6	25.18
2	365.	1.	0.0	0.177	129.4	117.5	105.0	24.36
3	367.	1.	0.0	0.176	128.6	117.4	105.1	23.55
4	364.	1.	0.0	0.175	127.4	117.5	105.4	21.99
5	366.	1.	0.0	0.174	126.6	117.5	105.6	20.96
6	373.	1.	0.0	0.173	126.0	117.5	105.8	20.25
7	377.	1.	0.0	0.171	125.2	117.7	106.0	19.18
8	387.	1.	0.0	0.171	123.6	117.8	106.1	17.50
9	391.	1.	0.0	0.195	139.9	119.7	107.7	32.22
10	346.	1.	0.0	0.389	270.8	126.5	112.2	158.64
11	280.	1.	0.0	0.563	389.9	130.9	115.4	274.56
12	215.	1.	0.0093	0.704	494.6	140.9	124.0	370.61
13	153.	1.	0.0270	0.836	595.1	148.4	130.1	464.96
14	56.	1.	0.0421	0.959	685.5	155.8	136.5	549.08
15	21.	1.	0.0583	1.137	766.6	161.4	141.6	625.00
16	9.	1.	0.0624	1.273	783.0	164.2	144.4	638.61
17	4.	1.	0.0458	1.187	665.8	153.0	134.5	531.34
18	2.	1.	0.0308	1.098	581.1	145.4	127.9	453.17
19	1.	1.	0.0	0.990	512.0	138.9	122.7	389.27
20	1.	1.	0.0	0.913	462.6	133.8	118.1	344.50
21	1.	1.	0.0	0.825	416.7	128.3	113.2	303.43
22	1.	1.	0.0	0.747	379.0	113.5	99.2	279.77
23	1.	1.	0.0	0.679	346.1	104.4	90.3	255.79
24	0.	1.	0.0	0.622	318.7	97.9	84.1	234.58
25	0.	1.	0.0	0.573	296.8	91.8	78.3	218.48

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 4
TEST DATE 6-9-82

PROCESSING DATE 6-11-82 ~~6-10-82~~
TEST DURATION, SEC 383.00

COMMENTS . . .

OVERRODE PIDS 29,30,31 AND 33.

AMBIENT PRESSURE			13.8000
LO2 VENTURI (GG)			
P/N V160248-SGR	UPSTREAM DIAMETER		0.0
S/N 8871	THROAT DIAMETER		0.0
	THROAT CD		0.0
GH2 VENTURI (TURB)			
P/N VP031200-SGR	UPSTREAM DIAMETER		2.3000
S/N 9731	THROAT DIAMETER		1.3085
	THROAT CD		0.9873
LH2 VENTURI (GG)			
P/N V320471-SGR	UPSTREAM DIAMETER		0.0
S/N 8873	THROAT DIAMETER		0.0
	THROAT CD		0.0
LH2 VENTURI (PUMP DISCH)			
P/N V320709-SGR	UPSTREAM DIAMETER		1.6890
S/N 8874	THROAT DIAMETER		0.7090
	THROAT CD		0.9760
	TURBINE SYSTEM EFF. AREA		0.70470
	TURBINE EXHAUST ORIFICE	4 EACH	0.31200
		4 EACH	0.32500
		1 EACH	0.30800

HYDROSTATIC BEARING SUPPLY SYSTEM

TURBINE	INLET DUCT DIA 0.334	ORIFICE DIA 0.194
PUMP	INLET DUCT DIA 0.402	ORIFICE DIA 0.175

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RUN NUMBER 4
TEST DATE 6-9-82

PROCESSING DATE 6-10-82
TEST DURATION, SEC 383.0C

G A S E O U S   H Y D R O G E N   T U R B I N E   D R I V E   P A R A M E T E R S

TIME SLICE NO	BEGIN TIME (SEC)	END TIME (SEC)	RFS U/S PR (PSIA)	VENTURI U/S PR (PSIA)	VENTURI U/S TEMP (DEG R)	VENTURI DELTA PR (PSID)	SPIN VALVE POSN	SPIN VALVE U/S PR (PSIA)	FAC DUCT PR (PSIA)	TURB GH2 FLOW (LB/SEC)	SPEED (RPM)
1	144.974	145.242	4754.6	4752.6	519.59	0.0	-0.15	4745.8	14.02	0.0008	960.
2	149.965	150.233	4745.8	4743.7	519.59	0.37	5.97	4736.8	14.02	0.6922	31680.
3	154.996	155.223	4706.1	4704.7	519.59	0.75	7.69	4696.4	14.02	0.9782	35752.
4	159.987	160.255	4679.3	4678.8	519.59	0.11	4.26	4671.6	14.02	0.3806	24218.
5	164.978	165.246	4658.6	4656.6	519.59	0.12	4.27	4649.6	14.02	0.3865	24449.
6	169.968	170.236	4639.6	4637.7	519.59	0.09	4.21	4630.7	14.02	0.3409	23479.
7	174.959	175.227	4617.4	4614.7	519.59	0.13	4.42	4607.2	14.02	0.3978	24817.
8	179.991	180.259	4595.7	4593.4	519.59	0.08	4.11	4586.1	14.02	0.3187	23206.
9	184.981	185.249	4577.0	4575.8	519.59	0.07	3.91	4568.2	14.02	0.2959	22308.
10	189.972	190.240	4559.0	4558.0	519.59	0.07	3.91	4550.8	14.02	0.2955	22328.
11	194.962	195.230	4541.5	4540.8	519.59	0.07	3.96	4533.3	14.02	0.2950	22324.
12	199.994	200.221	4523.6	4523.6	519.59	0.07	4.04	4515.9	14.00	0.2946	22512.
13	204.985	205.253	4507.7	4504.9	519.59	0.08	4.11	4497.7	14.02	0.3123	22831.
14	209.975	210.243	4486.0	4485.6	519.59	0.13	4.55	4478.3	14.01	0.3733	24697.
15	214.966	215.234	4466.0	4465.4	519.59	0.13	4.54	4456.9	14.02	0.3925	24658.
16	219.998	220.225	4446.0	4445.7	519.59	0.07	3.92	4438.3	14.02	0.2925	22119.
17	319.974	320.242	4065.6	4066.6	519.59	0.09	4.29	4056.2	14.02	0.3195	22753.
18	329.997	330.223	4033.1	4033.1	519.59	0.07	4.13	4024.0	14.02	0.2810	22811.
19	339.978	340.246	4000.2	4000.0	519.59	0.07	4.11	3990.0	14.02	0.2840	23309.
20	349.959	350.227	3965.7	3965.0	519.59	0.07	4.10	3957.1	14.01	0.2868	23351.
21	359.981	360.249	3933.4	3934.1	519.59	0.03	3.48	3924.7	14.02	0.1821	21143.
22	369.963	370.231	3911.0	3912.0	519.59	-0.00	3.05	3903.5	14.02	0.0	18177.
23	379.985	380.253	3891.7	3892.7	519.59	-0.02	-0.20	3882.0	14.02	0.0	14644.

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RUN NUMBER 4
TEST DATE 6-9-82

PROCESSING DATE 6-10-82
TEST DURATION, SEC 383.00

HYBRID BEARING DATA
PUMP - END (PAGE 1)

TIME SLICE NO	PUMP BRG SUPPLY U/S PRESS (PSIA)	PUMP BRG SUPPLY TEMP (DEG R)	PUMP BRG SUPPLY D/S ORIF PRESS (PSIA)	PUMP BRG SUPPLY ORIF DP (PSID)	PUMP BRG SUPPLY MANIF PRESS (PSIA)	--- PUMP BRG PAD PRESSURES --- 3.00 OCLOCK (PSIA)	9.00 OCLOCK (PSIA)	6.30 OCLOCK (PSIA)
1	379.7	70.0	362.8	24.7	374.5	141.9	140.1	14.9
2	496.1	72.3	467.0	36.7	478.9	181.6	178.0	14.5
3	554.4	72.5	521.8	39.5	534.5	228.9	229.5	14.1
4	461.2	70.4	435.7	34.0	447.8	179.4	180.0	13.8
5	466.4	69.6	438.3	34.9	451.6	178.9	179.4	13.8
6	460.8	68.8	433.7	34.9	446.1	175.6	176.2	13.4
7	472.8	68.5	443.8	36.1	455.8	179.9	179.9	13.2
8	462.9	68.3	435.6	35.3	447.6	175.4	175.4	13.1
9	454.1	68.1	427.3	34.4	439.2	171.9	171.3	13.3
10	453.3	68.0	426.0	34.1	438.8	170.6	170.6	13.2
11	454.5	68.0	428.2	34.1	439.5	171.9	171.3	13.3
12	454.1	68.0	426.8	34.0	438.9	171.4	171.5	13.3
13	459.0	68.0	430.5	34.1	442.5	173.1	173.5	13.1
14	469.3	68.3	441.8	35.2	453.2	178.9	179.6	13.3
15	468.7	68.2	441.0	35.0	453.1	178.5	178.8	13.2
16	454.1	68.0	427.7	33.5	439.7	171.6	171.0	13.5
17	449.7	72.9	428.4	27.7	440.9	177.6	177.6	13.4
18	846.5	78.6	781.6	67.0	794.9	275.7	274.9	12.9
19	1058.1	77.3	970.1	90.2	982.3	311.6	308.0	13.1
20	1058.3	75.3	968.3	92.2	980.4	292.1	303.9	13.0
21	1048.2	75.0	958.8	91.7	970.9	285.1	292.1	13.0
22	1030.6	75.1	943.0	90.0	955.0	285.4	285.4	13.3
23	1019.9	75.4	934.3	88.7	946.5	284.4	278.6	13.0

ORIGINAL PAGE IS
OF POOR QUALITY

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 4
TEST DATE 6-9-82

PROCESSING DATE 6-10-82
TEST DURATION, SEC 383.00

H Y B R I D   B E A R I N G   D A T A
PUMP - END (PAGE 2)

TIME SLICE NO	PUMP BRG SUMP PRESSURE (PSIA)	PUMP BRG SUMP OUT PRESSURE (PSIA)	PUMP BRG SUMP OUT TEMP (DEG R)	SHAFT SPEED (RPM)	CARTRIDGE SPEED (RPM)	PUMP BRG FLOW (LB/SEC)	LH2 DENSITY AT ORIF (PCF)	AVERAGE PAD PRESSURE (PSIA)	PUMP BRG PRESSURE RATIO
1	108.2	48.8	75.6	960.	1304.	0.0826	2.1761	141.0	0.1234
2	107.1	50.7	79.6	31680.	9772.	0.1097	2.5787	179.8	0.1956
3	104.9	51.0	75.6	35752.	35846.	0.1180	2.7771	229.2	0.2894
4	107.6	51.0	79.6	24218.	24218.	0.1067	2.6345	179.7	0.2120
5	106.1	50.8	79.6	24449.	24449.	0.1104	2.7498	179.1	0.2114
6	107.8	51.5	79.6	23479.	23512.	0.1118	2.8167	175.9	0.2012
7	106.4	51.4	79.6	24817.	24817.	0.1151	2.8877	179.9	0.2104
8	108.1	51.9	79.6	23206.	23175.	0.1136	2.8786	175.4	0.1981
9	107.2	51.4	75.6	22308.	22290.	0.1118	2.8636	171.6	0.1940
10	105.9	51.1	75.6	22328.	22342.	0.1115	2.8702	170.6	0.1944
11	107.6	51.6	79.6	22324.	22323.	0.1117	2.8765	171.6	0.1928
12	106.6	51.2	79.6	22512.	22544.	0.1114	2.8730	171.4	0.1951
13	108.4	51.9	79.6	22831.	22862.	0.1118	2.8883	173.3	0.1943
14	106.9	51.6	79.6	24697.	24697.	0.1139	2.9008	179.3	0.2090
15	105.7	51.4	79.6	24658.	24659.	0.1137	2.9054	178.6	0.2099
16	107.9	51.8	79.6	22119.	22128.	0.1106	2.8730	171.3	0.1911
17	106.0	49.8	79.6	22753.	22758.	0.0897	2.2831	177.6	0.2137
18	109.0	50.4	79.6	22811.	22832.	0.1608	3.0367	275.3	0.2424
19	111.0	50.6	79.6	23309.	23325.	0.1973	3.3983	309.8	0.2282
20	109.9	50.4	79.6	23351.	23350.	0.2022	3.4910	298.0	0.2161
21	111.4	51.0	79.6	21143.	21119.	0.2018	3.4973	288.6	0.2062
22	110.1	50.4	79.6	18177.	18208.	0.1992	3.4718	285.4	0.2075
23	114.7	52.8	79.6	14644.	14512.	0.1971	3.4477	281.5	0.2005

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H Y B R I D   B E A R I N G   D A T A
PUMP - END (PAGE 3)

TIME SLICE NO	BRG DELTA P ORIFICE PSID	BRG DELTA P FILM PSID	BRG DELTA P TOTAL PSID	ORIFICE RESISTANCE SEC**2/ LB-IN**2	FLUID FILM RESISTANCE SEC**2/ LB-IN**2	POISEUILLE RENOLDS NO	COUETTE RENOLDS NO	LAMBDA BRG NO	TORQUE FLUID FILM (TEMP) IN-LBS
1	233.4	32.8	266.3	34180.9	4809.7	73704664.	533.	0.00009	778.2472
2	295.1	72.7	371.7	24858.4	6042.8	101239278.	4220.	0.00056	145.8350
3	305.3	124.3	429.6	21929.5	8932.7	99343485.	16209.	0.00229	44.6314
4	268.1	72.1	340.3	23561.1	6338.1	83998388.	10351.	0.00163	60.6060
5	272.4	73.0	345.5	22342.3	5989.7	83944013.	10429.	0.00166	64.8174
6	270.2	68.0	338.2	21633.0	5448.0	83503487.	10165.	0.00161	70.3530
7	275.9	73.5	349.4	20827.3	5548.6	83919143.	10699.	0.00171	69.9378
8	272.2	67.3	339.5	21091.1	5211.6	84155402.	10097.	0.00159	74.1812
9	267.6	64.4	332.0	21402.3	5152.2	83395901.	9683.	0.00153	75.9861
10	268.1	64.7	332.8	21551.6	5199.6	83341283.	9652.	0.00153	75.8467
11	267.9	64.0	331.9	21482.1	5130.0	83531842.	9730.	0.00153	76.1389
12	267.5	64.8	332.3	21557.6	5225.2	83128729.	9770.	0.00155	75.0962
13	269.2	64.9	334.1	21548.8	5198.2	83587991.	9992.	0.00157	74.3780
14	273.9	72.4	346.3	21109.6	5577.4	83431591.	10694.	0.00171	70.1230
15	274.5	72.9	347.4	21245.1	5644.0	83375747.	10673.	0.00170	70.2346
16	268.4	63.4	331.8	21934.8	5182.5	83813373.	9657.	0.00152	75.9845
17	263.3	71.6	334.9	32741.3	8898.4	81709142.	9304.	0.00151	46.8550
18	519.6	166.2	685.8	20105.4	6432.7	163082822.	10411.	0.00096	86.6390
19	672.4	198.8	871.3	17270.4	5105.9	211165425.	11523.	0.00094	111.5376
20	682.3	188.2	870.5	16697.1	4604.2	217210900.	11761.	0.00084	120.3973
21	682.3	177.2	859.5	16756.7	4353.2	224654269.	10769.	0.00074	134.0060
22	669.6	175.4	844.9	16870.2	4418.0	224379596.	9242.	0.00064	152.5321
23	665.1	166.8	831.9	17117.8	4293.4	228767536.	7451.	0.00050	187.9506

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LIQUID HYDROGEN TURBOPUMP ASSEMBLY

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H Y B R I D   B E A R I N G   D A T A
PUMP AND TURBINE END (PAGE 4)

	- - PUMP - -			- - TURBINE - -					
TIME SLICE NO	HS BRG CLEARANCE RADIAL IN	VISCOSITY PUMP BRG LB-HR/FT**2 * E10	CSUBP PUMP BRG BTU/ LB-R	HS BRG CLEARANCE RADIAL IN	VISCOSITY TURB BRG LB-HR/FT**2 * E10	CSUBP TURB BRG BTU/ LB-R	POISEUILLE RENOLDS NO	COUETTE RENOLDS NO	LAMBDA TURB NO
1	0.00246	0.12992	3.4356	0.00246	0.13626	10.0770	70906662.	0.	0.0
2	0.00244	0.13732	3.7466	0.00245	0.23649	5.8593	84888237.	1471.	0.0002
3	0.00226	0.14624	4.5287	0.00246	0.30467	4.2363	152674619.	266.	0.0000
4	0.00236	0.14091	1.9542	0.00246	0.23833	5.2597	124564276.	13.	0.0000
5	0.00236	0.14268	4.0526	0.00246	0.24852	5.1554	116872498.	44.	0.0000
6	0.00237	0.14311	4.1077	0.00246	0.24529	5.3045	106580426.	7.	0.0000
7	0.00236	0.14558	4.2340	0.00246	0.26526	4.9169	112308962.	177.	0.0000
8	0.0[illegible]37	0.14392	4.1772	0.00246	0.25409	5.0894	109551950.	44.	0.0000
9	0.00237	0.14230	4.1230	0.00246	0.24443	5.3466	101839878.	13.	0.0000
10	0.00237	0.14191	4.1153	0.00246	0.24430	5.3773	99811882.	35.	0.0000
11	0.00237	0.14247	4.1391	0.00246	0.24490	5.3681	99703125.	85.	0.0000
12	0.00237	0.14234	4.1326	0.00246	0.24644	5.3213	100744195.	549.	0.0001
13	0.00237	0.14379	4.1693	0.00246	0.24962	5.2613	101323912.	239.	0.0000
14	0.00236	0.14587	4.2632	0.00246	0.26506	4.9677	106893174.	363.	0.0000
15	0.00236	0.14569	4.2598	0.00246	0.26646	4.9216	109402830.	588.	0.0001
16	0.00238	0.14228	4.1302	0.00246	0.24705	5.2869	102311502.	471.	0.0001
17	0.00237	0.13753	3.6656	0.00246	0.20108	6.1404	120213524.	519.	0.0001
18	0.00237	0.15732	4.2576	0.00246	0.27641	4.0362	259749957.	1.	0.0000
19	0.00237	0.16676	4.9572	0.00246	0.35298	3.3979	351546186.	1.	0.0000
20	0.00237	0.16511	5.2624	0.00246	0.37194	3.3062	347981265.	1.	0.0000
21	0.00238	0.16153	5.1775	0.00246	0.36972	3.3081	351405998.	1.	0.0000
22	0.00240	0.16052	5.0752	0.00246	0.34794	3.4234	342195231.	1.	0.0000
23	0.00242	0.15921	4.9327	0.00246	0.33881	3.4498	351921393.	1.	0.0000

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H Y B R I D   B E A R I N G   D A T A
TURBINE END (PAGE 1)

TIME SLICE NO	TURB BRG SUPPLY U/S PRESS (PSIA)	TURB BRG SUPPLY U/S TEMP (DEG R)	TURB BRG SUPPLY D/S ORIF PRESS (PSIA)	TURB BRG SUPPLY ORIF DP (PSID)	TURB BRG SUPPLY MANIF PRESS (PSIA)	TURB BRG DISCH PRESS (PSIA)	TURB BRG SUMP PRESS (PSIA)	-- TURBINE BRG -- DISCHARGE PRESS (PSIA)	LINE TEMP (DEG R)
1	312.8	68.1	301.9	15.3	288.2	120.4	99.8	35.6	459.6
2	642.5	74.9	620.1	34.9	583.8	346.0	322.3	97.6	79.6
3	977.6	75.2	937.7	60.0	866.4	416.6	390.5	110.3	79.6
4	716.3	73.3	682.1	45.0	628.9	262.7	238.6	73.9	79.6
5	706.5	72.0	673.8	42.6	620.1	264.2	240.0	75.9	79.6
6	660.6	70.8	630.8	39.8	581.3	254.1	231.0	73.1	79.6
7	708.9	70.5	676.7	41.9	622.3	268.5	245.3	79.2	79.6
8	677.6	70.2	646.2	41.5	594.5	253.5	229.7	73.8	79.6
9	638.1	69.9	606.0	40.3	559.7	242.1	219.0	70.8	79.6
10	631.2	69.7	601.3	38.5	554.2	240.8	218.2	70.8	79.6
11	632.3	69.7	603.9	38.0	555.1	242.1	219.3	71.4	79.6
12	637.9	69.7	606.0	39.9	559.7	243.6	219.6	71.9	79.6
13	644.3	69.8	615.1	37.5	567.0	248.8	225.2	72.2	79.6
14	690.5	70.0	659.4	40.5	606.6	268.4	245.8	76.0	79.6
15	700.9	70.1	669.2	43.0	614.7	267.6	245.8	76.6	79.6
16	642.8	69.8	612.7	38.9	563.9	241.1	219.1	71.2	79.6
17	636.9	76.4	608.0	35.1	566.4	244.4	220.7	69.3	79.6
18	1194.9	79.5	1133.5	75.3	1032.8	275.0	246.0	71.2	79.6
19	1601.0	75.8	1516.1	102.9	1371.6	295.6	265.2	79.6	79.6
20	1611.8	73.3	1525.0	103.6	1377.0	279.2	265.5	76.6	79.6
21	1592.9	73.0	1505.9	102.5	1359.9	277.4	247.2	72.2	79.6
22	1485.3	73.7	1406.5	94.9	1272.4	251.3	219.5	68.5	79.6
23	1468.0	74.1	1351.9	92.9	1240.1	212.9	183.3	61.9	79.6

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H Y B R I D   B E A R I N G   D A T A
TURBINE END (PAGE 2)

TIME SLICE NO	SHAFT SPEED (RPM)	TURBINE CARTRIDGE SPEED (RPM)	TURBINE H/S BRG FLOW (LB/SEC)	LH2 DENSITY AT ORIF (PCF)	TURB BRG SUPPLY MANIF PRESS (PSIA)	TURB BRG DISCH PRESS (PSIA)	TURB BRG SUMP PRESS (PSIA)	HYDROSTATIC BEARING DELTA PRESS (PSID)
1	960.	0.	0.0837	1.819	288.2	120.4	99.8	188.46
2	31680.	2295.	0.1578	2.844	583.8	346.0	322.3	261.50
3	35752.	327.	0.2265	3.406	866.4	416.6	390.5	475.89
4	24218.	21.	0.1876	3.118	628.9	262.7	238.6	390.24
5	24449.	70.	0.1846	3.185	620.1	264.2	240.0	380.19
6	23479.	12.	0.1782	3.180	581.3	254.1	231.0	350.26
7	24817.	269.	0.1859	3.289	622.3	268.5	245.3	377.01
8	23206.	69.	0.1841	3.252	594.5	253.5	229.7	364.82
9	22308.	21.	0.1799	3.201	559.7	242.1	219.0	340.72
10	22328.	58.	0.1757	3.197	554.2	240.8	218.2	336.00
11	22324.	140.	0.1746	3.199	555.1	242.1	219.3	335.84
12	22512.	902.	0.1794	3.210	559.7	243.6	219.6	340.11
13	22831.	387.	0.1740	3.218	567.0	248.8	225.2	341.78
14	24697.	555.	0.1826	3.285	606.6	268.4	245.8	360.86
15	24658.	892.	0.1895	3.297	614.7	267.6	245.8	368.89
16	22119.	771.	0.1773	3.217	563.9	241.1	219.1	344.89
17	22753.	891.	0.1546	2.711	566.4	244.4	220.7	345.67
18	22811.	1.	0.2554	3.450	1032.8	275.0	246.0	786.83
19	23309.	1.	0.3179	3.912	1371.6	295.6	265.2	1106.37
20	23351.	1.	0.3224	3.999	1377.0	299.2	265.5	1111.47
21	21143.	1.	0.3208	4.000	1359.9	277.4	247.2	1112.73
22	18177.	1.	0.3051	3.907	1272.9	251.3	219.5	1052.90
23	14644.	1.	0.3010	3.884	1260.1	212.9	183.3	1076.78

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LIQUID HYDROGEN TURBOPUMP ASSEMBLY

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COMMENTS . . .

SLICES 34 TO 62.

AMBIENT PRESSURE		13.8000
LO2 VENTURI (GG) P/N V160248-SGR S/N 8871	UPSTREAM DIAMETER	0.0
	THROAT DIAMETER	0.0
	THROAT CD	0.0
GH2 VENTURI (TURB) P/N VP031200-SGP S/N 9731	UPSTREAM DIAMETER	2.3000
	THROAT DIAMETER	1.3085
	THROAT CD	0.9873
LH2 VENTURI (GG) P/N V320471-SGR S/N 8873	UPSTREAM DIAMETER	0.0
	THROAT DIAMETER	0.0
	THROAT CD	0.0
LH2 VENTURI (PUMP DISCH) P/N V320709-SGR S/N 8874	UPSTREAM DIAMETER	1.6890
	THROAT DIAMETER	0.7090
	THROAT CD	0.9760

TURBINE SYSTEM EFF. AREA 0.70470
TURBINE EXHAUST ORIFICE 4 EACH 0.31200
4 EACH 0.32500
1 EACH 0.30800

HYDROSTATIC BEARING SUPPLY SYSTEM
TURBINE INLET DUCT DIA 0.334 ORIFICE DIA 0.194
PUMP INLET DUCT DIA 0.402 ORIFICE DIA 0.175

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

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G A S E O U S   H Y D R O G E N   T U R B I N E   D R I V E   P A R A M E T E R S

TIME SLICE NO	BEGIN TIME (SEC)	END TIME (SEC)	REG U/S PR (PSIA)	VENTURI U/S PR (PSIA)	VENTURI U/S TEMP (DEG R)	VENTURI DELTA PR (PSID)	SPIN VALVE POSN	SPIN VALVE U/S PR (PSIA)	FAC DUCT PR (PSIA)	TURB GH2 FLOW (LB/SEC)	SPEED (RPM)
1	89.996	90.223	4787.9	4788.8	530.72	0.0	-0.83	4781.5	13.72	0.0015	1465.
2	99.977	100.245	4778.3	4779.0	530.49	0.0	-0.84	4771.0	13.70	0.0015	1307.
3	109.999	110.226	4763.5	4763.9	530.07	0.0	-0.84	4756.1	13.72	0.0014	1287.
4	119.980	120.249	4760.4	4761.6	530.17	0.0	-0.85	4753.4	13.73	0.0014	1355.
5	129.962	130.230	4758.7	4758.1	530.22	0.0	-0.85	4749.9	13.71	0.0014	1307.
6	131.983	132.127	4748.4	4748.9	529.82	0.12	4.06	4740.4	13.67	0.3889	35000.
7	134.993	135.138	4724.4	4724.8	531.46	0.47	6.15	4714.8	13.70	0.7852	34000.
8	137.953	138.149	4698.9	4699.9	532.27	0.49	6.22	4689.4	13.72	0.8005	33000.
9	140.974	141.159	4677.7	4678.1	533.07	0.33	5.52	4668.5	13.71	0.6563	31000.
10	143.985	144.129	4654.9	4654.9	533.97	0.47	6.16	4644.9	13.72	0.7789	33000.
11	146.996	147.149	4631.4	4631.8	534.65	0.44	6.03	4622.2	13.70	0.7559	33000.
12	149.965	150.151	4608.6	4608.1	535.02	0.45	6.16	4598.2	13.71	0.7637	33000.
13	152.976	153.120	4586.3	4586.2	535.24	0.41	6.00	4575.9	13.74	0.7246	34000.
14	155.987	156.131	4562.3	4562.5	535.45	0.48	6.32	4553.1	13.72	0.7815	33543.
15	158.998	159.142	4540.0	4540.9	535.62	0.39	5.97	4530.2	13.74	0.7097	34000.
16	161.967	162.153	4517.8	4517.9	535.89	0.50	6.35	4508.4	13.71	0.8020	33690.
17	164.978	165.123	4490.1	4492.2	535.96	0.39	6.00	4482.6	13.74	0.7007	34000.
18	167.989	168.133	4461.1	4460.9	536.32	0.49	6.35	4450.8	13.74	0.7882	33909.
19	170.959	171.144	4424.7	4426.9	536.67	0.41	6.03	4417.1	13.78	0.7175	33000.
20	173.969	174.155	4401.8	4402.5	536.70	0.48	6.35	4392.5	13.74	0.7758	33464.
21	176.980	177.125	4369.7	4371.1	536.85	0.47	6.29	4361.3	13.74	0.7655	33240.
22	179.991	180.135	4353.4	4353.5	536.92	0.45	6.34	4343.6	13.79	0.7486	33214.
23	182.961	183.146	4330.1	4331.3	537.15	0.49	6.54	4321.2	13.76	0.7824	33708.
24	185.972	186.157	4308.0	4308.6	537.21	0.41	6.15	4299.7	13.76	0.7091	33000.
25	188.982	189.127	4285.5	4286.3	537.29	0.51	6.67	4276.0	13.75	0.7945	34688.
26	191.993	192.138	4265.6	4267.1	537.44	0.0	-0.87	4275.1	13.77	0.0021	22860.
27	194.963	195.148	4264.7	4265.8	536.79	0.0	-0.92	176.2	13.78	0.0020	10549.
28	197.974	198.159	4265.3	4266.2	536.65	0.0	-0.91	17.1	13.76	0.0020	6253.
29	200.985	201.129	4266.4	4266.6	536.54	0.0	-0.91	13.1	13.77	0.0020	4325.

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HYBRID BEARING DATA
PUMP - END (PAGE 1)

TIME SLICE NO	PUMP BRG SUPPLY U/S PRESS (PSIA)	PUMP BRG SUPPLY TEMP (DEG R)	PUMP BRG SUPPLY D/S ORIF PRESS (PSIA)	PUMP BRG SUPPLY ORIF DP (PSID)	PUMP BRG SUPPLY MANIF PRESS (PSIA)	PUMP BRG PAD PRESSURES 3.00 OCLOCK (PSIA)	9.00 OCLOCK (PSIA)	6.30 OCLOCK (PSIA)
1	113.4	108.5	118.5	4.3	128.4	108.8	109.4	13.2
2	364.9	111.4	347.3	24.1	358.7	142.7	140.1	13.6
3	379.4	80.4	362.1	25.1	372.3	141.3	139.9	13.7
4	379.7	74.0	362.3	25.8	372.6	154.5	154.6	13.7
5	380.0	72.1	362.5	26.5	372.5	143.0	142.7	13.4
6	470.4	74.6	443.6	34.5	455.7	172.5	172.8	13.7
7	523.3	75.1	491.1	38.8	502.5	199.5	[illegible]	13.0
8	528.3	74.8	498.2	37.3	509.9	212.3	214.4	13.1
9	507.8	73.8	476.9	38.3	487.5	196.3	198.9	13.0
10	523.0	73.4	492.0	38.4	503.0	207.1	209.3	13.3
11	516.9	71.9	484.6	40.2	493.9	199.9	202.6	13.3
12	524.2	71.2	491.3	40.9	502.5	203.2	205.3	13.2
13	536.2	70.7	502.6	40.6	513.8	211.0	213.7	13.3
14	543.4	70.2	510.2	40.2	521.6	217.5	219.9	13.3
15	536.0	69.7	501.2	[illegible]	512.7	209.7	211.3	13.4
16	544.4	69.5	511.6	40.0	523.0	218.5	220.9	13.3
17	553.9	70.1	517.2	43.4	528.9	213.0	214.9	13.5
18	554.6	72.0	521.5	39.2	531.9	221.0	224.7	13.1
19	541.9	73.4	509.5	38.4	521.3	215.6	218.2	13.4
20	544.1	74.7	512.9	36.6	524.0	219.2	222.9	13.1
21	547.6	75.0	515.7	37.2	527.4	219.5	223.7	13.3
22	541.4	75.5	510.5	36.2	522.3	217.3	221.4	13.5
23	540.6	75.5	511.9	34.7	523.2	220.4	224.8	13.1
24	583.4	76.4	546.6	41.5	558.7	227.0	230.6	12.8
25	1015.2	80.1	933.6	84.3	945.2	327.7	332.7	13.3
26	1148.2	80.5	1051.1	98.8	1061.1	322.6	324.9	13.7
27	457.4	64.4	428.6	36.7	438.7	157.3	155.6	13.7
28	173.3	56.9	174.6	7.0	184.7	66.0	63.6	13.7
29	151.4	57.4	153.4	6.6	162.8	55.0	52.8	13.2

ORIGINAL PAGE IS
OF POOR QUALITY

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 6
TEST DATE 6-14-82

PROCESSING DATE 6-22-82
TEST DURATION, SEC 203.00

HYBRID BEARING DATA
PUMP - END (PAGE 2)

TIME SLICE NO.	PUMP BRG SUMP PRESSURE (PSIA)	PUMP BRG SUMP OUT PRESSURE (PSIA)	PUMP BRG SUMP OUT TEMP (DEG R)	SHAFT SPEED (RPM)	CARTRIDGE SPEED (RPM)	PUMP BRG FLOW (LB/S)	LH2 DENSITY AT ORIF (PCF)	AVERAGE PAD PRESSURE (PSIA)	PUMP BRG PRESSURE RATIO
1	106.2	54.9	45.5	1465.	1362.	0.0105	0.2032	109.2	0.1362
2	107.4	45.4	44.9	1307.	1243.	0.0455	0.6764	141.4	0.1353
3	106.8	46.4	44.9	1287.	1234.	0.0640	1.2854	140.6	0.1272
4	106.7	46.9	45.0	1355.	1045.	0.0744	1.6089	154.5	0.1800
5	106.5	47.2	45.0	1307.	1238.	0.0798	1.8945	142.8	0.1366
6	108.0	49.6	45.4	35000.	11660.	0.0984	2.2066	172.6	0.1858
7	106.4	50.5	45.6	34000.	27863.	0.1092	2.4219	200.5	0.2376
8	105.1	50.2	45.6	33000.	32453.	0.1082	2.4672	213.4	0.2674
9	106.7	50.5	45.6	31000.	30063.	0.1098	2.4798	197.6	0.2388
10	105.6	50.5	45.6	33000.	32015.	0.1122	2.5833	208.2	0.2581
11	104.5	50.3	45.6	33000.	31313.	0.1176	2.7061	201.2	0.2472
12	106.4	51.3	45.7	33000.	31747.	0.1207	2.8042	204.2	0.2471
13	106.1	51.3	45.7	34000.	32812.	0.1220	2.8870	212.3	0.2606
14	105.9	51.4	45.7	33543.	33558.	0.1228	2.9510	218.7	0.2716
15	106.1	51.5	45.8	34000.	32581.	0.1242	2.9717	210.5	0.2568
16	106.4	51.8	45.9	33690.	33662.	0.1237	3.0158	219.7	0.2719
17	105.7	51.5	45.8	34000.	32645.	0.1203	2.9887	213.9	0.2558
18	105.1	50.9	45.7	33909.	33920.	0.1187	2.8284	222.9	0.2760
19	107.3	51.3	45.7	33000.	32937.	0.1138	2.6529	216.9	0.2648
20	106.1	50.5	45.6	33464.	33397.	0.1087	2.5399	227.0	0.2749
21	105.4	50.4	45.5	33240.	33708.	0.1092	2.5244	221.6	0.2754
22	107.6	50.9	45.6	33214.	33037.	0.1064	2.4508	219.4	0.2695
23	106.2	50.5	45.6	33708.	33674.	0.1041	2.4582	222.6	0.2791
24	106.1	50.2	45.6	33000.	32696.	0.1155	2.5377	228.8	0.2709
25	109.2	50.5	45.6	34688.	34768.	0.1855	3.2151	330.2	0.2643
26	115.9	116.7	53.7	27860.	27719.	0.2053	3.3583	323.7	0.2199
27	107.1	48.5	45.3	10549.	10502.	0.1228	3.7369	156.5	0.1487
28	53.9	30.4	41.8	6253.	6277.	0.0314	1.1079	64.8	0.0841
29	42.6	26.5	40.8	4125.	4349.	0.0271	0.8852	53.9	0.0945

ORIGINAL PAGE IS
OF POOR QUALITY

RUN NUMBER 6
TEST DATE 6-14-82

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H Y B R I D B E A R I N G D A T A
PUMP - END (PAGE 3)

TIME SLICE NO	BRG DELTA P ORIFICE PSID	BRG DELTA P FILM PSID	BRG DELTA P TOTAL PSID	ORIFICE RESISTANCE SEC**2/ LB-IN**2	FLUID FILM RESISTANCE C**2/ LB-IN**2	POISEUILLE RENOLDS NO	COUETTE RENOLDS NO	LAMBDA BRG NO	TORQUE FLUID FILM (EMP) IN-LBS
1	19.2	3.0	22.2	174241.1	27468.4	1698743.	204.	0.00036	-233.0402
2	217.3	34.0	251.3	104919.5	16419.1	20497621.	204.	0.00012	-488.3818
3	231.7	33.8	265.5	56549.1	8240.0	50556515.	377.	0.00009	-152.6658
4	218.1	47.9	265.9	39406.5	8640.6	65843637.	398.	0.00008	30.1127
5	229.7	36.3	266.0	36077.1	5705.9	68678174.	478.	0.00009	112.9218
6	283.1	64.6	347.6	29244.1	6673.1	85345390.	4612.	0.00072	18.6518
7	301.9	94.1	396.0	25309.7	7887.2	90473945.	11374.	0.00193	11.1234
8	296.5	108.7	404.8	25343.9	9249.2	89813577.	13500.	0.00208	10.4074
9	289.9	90.9	380.8	24026.9	7537.4	88281678.	17520.	0.00193	12.4842
10	294.9	102.6	397.4	23406.3	8144.2	92111226.	13693.	0.00205	13.7034
11	294.7	96.7	391.4	21306.8	6994.9	95309500.	13727.	0.00198	17.6952
12	298.2	97.9	396.1	20472.9	6720.7	99462326.	14414.	0.00199	19.8657
13	301.5	106.2	407.7	20247.1	7136.0	103372491.	15331.	0.00205	20.8947
14	302.8	112.9	415.7	20081.3	7486.0	106108395.	16050.	0.00210	21.7202
15	302.2	104.4	406.6	19578.2	6765.2	10629417 .	15586.	0.00203	23.4324
16	303.3	113.2	416.5	19818.5	7401.0	108251725.	16461.	0.00211	23.3310
17	314.9	108.2	423.2	19118.9	6570.2	109311015.	15545.	0.00199	23.8343
18	309.0	117.8	426.8	21948.3	8368.1	103013586.	15532.	0.00211	17.7655
19	304.4	109.6	414.0	23516.0	8471.0	96399970.	14426.	0.00207	14.1776
20	303.0	114.9	417.9	25642.6	9721.0	93246243.	14201.	0.00212	11.0138
21	305.8	116.3	422.1	25634.8	9744.9	93362320.	14000.	0.00209	10.6013
22	303.0	111.8	414.7	26769.9	9877.9	91252481.	13819.	0.00210	9.2872
23	300.6	116.4	417.0	27740.7	10740.6	91085580.	14103.	0.00215	9.0503
24	330.0	122.6	452.6	24677.6	9168.1	98061494.	13624.	0.00196	10.1032
25	615.0	221.0	836.0	17871.6	6421.1	169569932.	15964.	0.00145	17.6661
26	737.4	207.9	94[illegible].2	17499.3	4937.9	220870166.	10919.	0.00077	-81.3389
27	282.3	49.3	331.6	18705.0	3268.5	102163661.	5070.	0.00065	98.8443
28	119.9	11.0	130.9	121900.0	11191.6	28926776.	1689.	0.00072	12.4786
29	108.9	11.4	120.2	147776.6	15420.7	23264472.	991.	0.00055	9.4879

RUN NUMBER 6
TEST DATE 6-14-82

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H Y B R I D B E A R I N G D A T A
PUMP AND TURBINE END (PAGE 6)

	PUMP			TURBINE					
TIME SLICE NO	HS BRG CLEARANCE RADIAL IN	VISCOSITY PUMP BRG LB-HR/FT**2 * E10	CSUMP PUMP BRG BTU/ LB-R	HS BRG CLEARANCE RADIAL IN	VISCOSITY TURB BRG LB-HR/FT**2 * E10	CSUMP TURB BRG BTU/ LB-R	POISEUILLE RENOLDS NO	COUETTE RENOLDS NO	LAMBDA TURB NO
1	0.00246	0.17256	2.7231	0.00246	0.19369	2.7737	516003.	0.	0.0000
2	0.00246	0.17740	2.7799	0.00246	0.19037	2.9350	11518354.	0.	0.0000
3	0.00246	0.14117	3.0328	0.00246	0.14910	3.9023	39998955.	3.	0.0000
4	0.00246	0.13533	3.3487	0.00246	0.13882	5.3733	53520085.	0.	0.0
5	0.00246	0.13155	3.3374	0.00246	0.14263	6.7253	54144711.	0.	0.0000
6	0.00243	0.13865	3.4870	0.00246	0.18530	6.6365	90537418.	70.	0.0000
7	0.00233	0.14220	3.7524	0.00245	0.23496	5.2038	130407429.	1399.	0.0001
8	0.00230	0.14421	3.9346	0.00245	0.25153	4.7852	152112839.	2837.	0.0003
9	0.00232	0.14070	3.8382	0.00246	0.24193	5.0203	142228667.	357.	0.0000
10	0.00230	0.14243	4.0297	0.00246	0.26058	4.7034	149742222.	787.	0.0001
11	0.00231	0.13972	4.1179	0.00245	0.26882	4.6478	143937196.	1205.	0.0001
12	0.00230	0.13985	4.2879	0.00245	0.28431	4.4640	144717016.	2081.	0.0002
13	0.00229	0.14134	4.5499	0.00246	0.30738	4.2306	148701353.	891.	0.0001
14	0.00229	0.14286	4.9272	0.00246	0.32159	4.0699	157490214.	469.	0.0000
15	0.00229	0.14067	4.7248	0.00246	0.32540	4.0295	160889086.	904.	0.0001
16	0.00228	0.14332	5.0586	0.00245	0.33732	3.9371	161368276.	1271.	0.0001
17	0.00229	0.14157	4.7207	0.00245	0.33753	3.8128	193268109.	1554.	0.0001
18	0.00228	0.14423	4.5126	0.00245	0.33208	3.7975	210420944.	1371.	0.0001
19	0.00229	0.14413	4.1594	0.00246	0.30141	4.1057	187116387.	616.	0.0000
20	0.00229	0.14548	4.0481	0.00246	0.29166	4.3263	175212481.	312.	0.0000
21	0.00229	0.14577	4.0170	0.00245	0.27769	4.3722	173266504.	1330.	0.0001
22	0.00229	0.14555	3.9384	0.00246	0.26962	4.4734	169279706.	445.	0.0000
23	0.00228	0.14606	3.9026	0.00245	0.27244	4.4129	173618449.	1888.	0.0002
24	0.00229	0.14764	3.9542	0.00246	0.26670	4.4474	178341819.	740.	0.0001
25	0.00227	0.17087	4.6899	0.00245	0.33946	3.5485	302876218.	3479.	0.0002
26	0.00237	0.16894	4.5472	0.00246	0.35278	3.3063	429897471.	5.	0.0000
27	0.00243	0.13541	4.4301	0.00246	0.10616	6.3596	90380344.	4.	0.0000
28	0.00245	0.10632	3.0461	0.00246	0.11503	10.1802	36366784.	3.	0.0000
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

RUN NUMBER 6
TEST DATE 6-14-82

PROCESSING DATE 6-22-82
TEST DURATION, SEC 203.00

HYBRID BEARING DATA
TURBINE END (PAGE 1)

TIME SLICE NO	TURB BRG SUPPLY U/S PRESS (PSIA)	TURB BRG SUPPLY U/S TEMP (DEG R)	TURB BRG SUPPLY D/S ORIF PRESS (PSIA)	TURB BRG SUPPLY ORIF DP (PSID)	TURB BRG SUPPLY MANIF PRESS (PSIA)	TURB BRG DISCH PRESS (PSIA)	TURB BRG SUMP PRESS (PSIA)	-- TURBINE BRG -- DISCHARGE LINE PRESS (PSIA)	TEMP (DEG R)
1	99.9	127.7	100.8	3.4	101.5	102.6	88.8	40.4	44.3
2	259.7	121.8	252.8	12.8	241.5	112.0	95.7	32.0	79.3
3	298.8	83.0	290.0	14.7	275.[illegible]	113.7	97.4	35.4	70.3
4	293.3	73.1	284.7	14.8	272.1	113.6	96.9	35.4	51.6
5	295.9	70.3	286.7	14.7	272.9	113.6	96.7	34.2	43.4
6	543.2	77.4	524.5	29.2	491.6	261.0	241.1	73.7	49.4
7	795.1	79.3	763.0	47.3	707.1	341.0	319.2	94.9	51.9
8	888.4	79.2	851.9	51.1	788.0	348.1	328.0	98.2	52.2
9	819.1	77.7	783.3	48.6	723.5	319.0	297.6	85.6	50.9
10	876.8	77.0	840.6	49.4	775.8	341.4	320.2	95.7	51.8
11	861.4	75.1	823.8	51.2	757.8	331.2	309.7	93.3	51.6
12	875.8	73.8	839.0	49.4	773.9	343.1	321.4	98.0	52.2
13	922.6	72.8	884.3	50.8	815.3	374.0	352.4	99.1	52.4
14	956.0	71.9	918.2	51.9	845.6	384.3	362.3	104.7	52.9
15	962.2	71.4	920.2	54.1	845.3	369.0	347.2	104.9	52.8
16	979.1	70.8	937.9	53.4	862.6	387.1	365.6	108.7	53.4
17	1078.1	71.5	1028.7	64.7	939.1	374.4	351.4	107.3	53.1
18	1165.4	73.9	1109.6	71.7	1015.7	395.4	372.4	110.0	53.3
19	1072.9	76.5	1025.7	63.3	940.7	384.6	361.7	105.3	53.0
20	1020.5	78.6	977.9	57.5	902.5	386.0	364.5	105.3	52.9
21	1010.4	78.8	968.1	57.6	892.3	380.9	359.6	105.5	52.9
22	990.3	79.6	947.5	56.5	874.8	391.8	359.8	101.2	52.6
23	1009.6	79.7	966.2	57.0	892.9	387.0	365.0	106.6	52.9
24	1011.3	80.1	9[illegible].8	59.4	889.4	374.3	351.7	102.6	52.6
25	1565.8	79.6	14[illegible].4	98.3	1350.8	425.2	396.1	117.5	54.1
26	1835.6	78.2	1737.5	119.4	1572.8	229.6	201.7	124.8	54.9
27	448.7	64.8	428.6	20.7	394.3	131.0	113.5	44.1	45.1
28	173.8	58.9	167.4	3.5	163.7	65.3	53.1	26.1	41.3
29	52.4	57.3	149.2	4.1	143.5	51.7	42.3	23.8	40.8

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 6
TEST DATE 6-14-82

PROCESSING DATE 6-22-82
TEST DURATION, SEC 203.00

H Y B R I D   B E A R I N G   D A T A
TURBINE END (PAGE 2)

TIME SLICE NO	SHAFT SPEED (RPM)	TURBINE CARTRIDGE SPEED (RPM)	TURBINE H/S BRG FLOW (LB/SEC)	LH2 DENSITY AT ORIF (PCF)	TURB BRG SUPPLY MANIF PRESS (PSIA)	TURB BRG DISCH PRESS (PSIA)	TURB BRG SUMP PRESS (PSIA)	HYDROSTATIC BEARING DELTA PRESS (PSID)
1	1465.	2.	0.0114	0.149	101.5	102.6	88.8	12.71
2	1307.	2.	0.0368	0.421	241.5	112.0	95.7	145.79
3	1287.	10.	0.0566	0.866	275.5	113.7	97.4	178.12
4	1355.	0.	0.0656	1.161	272.1	113.6	96.9	175.21
5	1307.	0.	0.0710	1.367	272.9	113.6	96.7	176.19
6	35000.	126.	0.1297	2.295	491.6	261.0	241.1	250.47
7	34000.	2172.	0.1855	2.896	[illegible]07.1	341.0	319.2	387.89
8	33000.	4075.	0.1986	3.075	708.0	348.1	328.0	459.94
9	31000.	531.	0.1925	3.039	723.5	319.0	297.6	425.91
10	33000.	1103.	0.1904	3.177	775.8	341.4	320.2	455.64
11	33000.	1672.	0.2065	3.254	757.0	331.2	309.7	448.16
12	33000.	2739.	0.2039	3.347	773.9	343.1	321.4	452.49
13	34000.	1082.	0.2100	3.457	815.3	374.0	352.4	462.87
14	33543.	536.	0.2146	3.539	845.6	384.3	362.3	483.37
15	34000.	917.	0.2203	3.572	865.3	369.0	347.2	498.05
16	33690.	1392.	0.2201	3.618	962.	387.1	365.6	497.04
17	34000.	1678.	0.2445	3.680	919.	374.4	351.4	587.67
18	33909.	1513.	0.2565	3.657	1015.7	395.4	372.4	643.28
19	33000.	759.	0.2343	3.453	940.7	384.6	361.7	578.96
20	33464.	408.	0.2182	3.295	902.5	386.0	364.5	538.03
21	33240.	1765.	0.2175	3.270	892.3	380.9	359.6	532.68
22	33214.	697.	0.2132	3.204	874.8	381.8	359.0	515.02
23	33708.	2524.	0.2148	3.226	892.7	387.0	365.0	527.89
24	33000.	1093.	0.2186	3.206	909.4	374.3	351.7	537.68
25	34689.	3861.	0.3065	3.759	1350.8	425.2	396.1	954.62
26	22860.	6.	0.2450	3.971	1572.8	229.6	201.7	1371.09
27	10549.	8.	0.1264	3.179	394.3	131.0	113.5	280.82
28	6253.	8.	0.0319	1.138	163.7	65.3	53.1	110.58
29	4325.	167.	0.0308	0.912	143.6	51.7	42.3	101.17

ORIGINAL PAGE IS
OF POOR QUALITY

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 7
TEST DATE 6-14-82

PROCESSING DATE 6-22-82
TEST DURATION, SEC 205.00

COMMENTS . . .

SLICES 70 THRU 88.

AMBIENT PRESSURE			13.8000
LO2 VENTURI (GG)			
P/N V160248-SGR	UPSTREAM DIAMETER		0.0
S/N 8871	THROAT DIAMETER		0.0
	THROAT CD		0.0
GH2 VENTURI (TURB)			
P/N VP031200-SGR	UPSTREAM DIAMETER		2.3000
S/N 9731	THROAT DIAMETER		1.3085
	THROAT CD		0.9873
LH2 VENTURI (GG)			
P/N V320471-SGR	UPSTREAM DIAMETER		0.0
S/N 8873	THROAT DIAMETER		0.0
	THROAT CD		0.0
LH2 VENTURI (PUMP DISCH)			
P/N V320709-SGR	UPSTREAM DIAMETER		1.6890
S/N 8874	THROAT DIAMETER		0.7090
	THROAT CD		0.9760
	TURBINE SYSTEM EFF. AREA		0.70470
	TURBINE EXHAUST ORIFICE	4 EACH	0.31200
		4 EACH	0.32500
		1 EACH	0.30800

HYDROSTATIC BEARING SUPPLY SYSTEM
TURBINE INLET DUCT DIA 0.334 ORIFICE DIA 0.194
PUMP INLET DUCT DIA 0.402 ORIFICE DIA 0.175

ORIGINAL PAGE IS
OF POOR QUALITY

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 7
TEST DATE 6-14-82

PROCESSING DATE 6-22-82
TEST DURATION, SEC 205.00

GASEOUS HYDROGEN TURBINE DRIVE PARAMETERS

TIME SLICE NO	BEGIN TIME (SEC)	END TIME (SEC)	REG U/S PR (PSIA)	VENTURI U/S PR (PSIA)	VENTURI U/S TEMP (DEG R)	VENTURI DELTA PR (PSID)	SPIN VALVE POSN	SPIN VALVE U/S PR (PSIA)	FAC DUCT PR (PSIA)	TURB GH2 FLOW (LB/SEC)	SPEED (RPM)
1	154.996	155.140	4403.3	4402.0	530.43	0.0	2.20	4391.0	13.67	0.0014	1445.
2	156.976	157.120	4393.3	4392.7	531.09	0.32	5.47	4381.0	13.67	0.6293	27405.
3	158.997	159.141	4376.9	4375.9	531.98	0.41	6.03	4364.8	13.67	0.7122	30866.
4	160.977	161.121	4362.1	4361.2	532.37	0.54	6.66	4349.3	13.67	0.8128	31900.
5	162.998	163.142	4347.[illegible]	434[illegible].2	532.75	[illegible].45	6.33	4334.4	13.67	0.7547	31633.
6	164.977	165.122	4333.5	4330.7	533.21	0.44	6.16	4319.4	13.65	0.7297	32168.
7	166.998	167.143	4316.3	4315.2	533.69	0.53	6.75	4302.7	13.67	0.8226	33097.
8	168.978	169.122	4301.4	4300.2	534.14	0.37	5.85	4288.3	13.67	0.6708	31743.
9	170.999	171.143	4279.6	4279.0	534.12	0.41	6.07	4267.3	13.67	0.7049	31993.
10	172.979	173.123	4255.6	4254.9	534.58	0.49	6.54	4243.1	13.67	0.7725	33479.
11	174.958	175.144	4236.1	4236.4	534.81	0.34	5.72	4224.8	13.67	0.6425	31322.
12	176.979	177.124	4213.6	4212.5	534.88	0.44	6.23	4200.2	13.69	0.7247	32252.
13	178.959	179.145	4195.6	4195.9	535.02	0.47	6.52	4183.1	13.67	0.7652	33262.
14	180.980	181.124	4188.4	4188.4	535.06	0.0	-0.87	4017.8	13.67	0.0018	14328.
15	182.960	183.145	4184.2	4183.7	534.61	0.0	-0.92	379.3	13.67	0.0017	2967.
16	184.981	185.125	4186.3	4185.4	534.23	0.0	-0.91	77.9	13.67	0.0017	1509.
17	186.961	187.146	4184.9	4183.6	534.05	0.0	-0.92	17.5	13.67	0.0017	1114.
18	188.982	189.126	4184.8	4184.4	533.84	0.0	-0.92	13.9	13.67	0.0016	119.
19	190.961	191.147	4184.5	4183.9	533.75	0.0	-0.91	13.5	13.67	0.0016	1.

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RUN NUMBER 7
TEST DATE 6-14-82

PROCESSING DATE 6-22-82
TEST DURATION, SEC 205.00

HYBRID BEARING DATA
PUMP - END (PAGE 1)

TIME SLICE NO	PUMP BRG SUPPLY U/S PRESS (PSIA)	PUMP BRG SUPPLY TEMP (DEG R)	PUMP BRG SUPPLY D/S ORIF PRESS (PSIA)	PUMP BRG SUPPLY ORIF DP (PSID)	PUMP BRG SUPPLY MANIF PRESS (PSIA)	--- PUMP BRG PAD PRESSURES --- 3.00 OCLOCK (PSIA)	9.00 OCLOCK (PSIA)	6.30 OCLOCK (PSIA)
1	379.4		362.4	25.3	373.7	150.8	150.2	-20.1
2	472.5	[illegible]	447.2	33.4	458.9	187.0	190.0	-20.1
3	509.0	77.2	482.0	35.4	492.7	201.4	204.6	-20.1
4	516.2	76.9	488.5	36.1	500.1	205.0	209.4	-20.0
5	515.7	76.9	487.8	36.9	499.4	204.2	207.2	-20.1
6	524.3	76.7	495.9	37.4	507.4	208.5	212.2	-20.1
7	541.4	76.7	514.3	34.8	526.1	225.9	230.6	-20.0
8	519.1	75.7	490.7	37.3	501.7	205.9	209.4	-20.1
9	548.6	77.2	516.3	39.7	528.0	213.4	217.1	-19.9
10	552.9	78.7	522.7	37.5	534.8	221.9	226.8	-20.1
11	526.3	78.9	496.8	37.1	508.8	205.8	208.8	-20.1
12	536.3	80.4	506.8	37.0	518.7	213.3	216.7	-20.1
13	535.9	80.3	507.6	35.2	519.5	219.4	225.2	-20.4
14	429.9	77.4	410.3	29.3	421.3	164.1	165.6	-20.1
15	365.8	73.0	350.2	24.5	362.2	146.5	148.2	-20.0
16	324.7	68.3	313.1	21.0	324.8	112.9	112.7	-19.5
17	305.6	66.2	295.9	19.5	307.2	105.6	103.6	-20.1
18	277.8	64.6	271.2	17.0	282.3	93.8	92.2	-20.1
19	253.3	63.4	248.4	14.7	259.9	85.7	82.2	-20.4

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 7
TEST DATE 6-14-82

PROCESSING DATE 6-22-82
TEST DURATION, SEC 205.00

H Y B R I D   B E A R I N G   D A T A
PUMP - (N.) (PAGE 2)

TIME SLICE NO	PUMP BRG SUMP PRESSURE (PSIA)	PUMP BRG SUMP OUT PRESSURE (PSIA)	PUMP BRG SUMP OUT TEMP (DEG R)	SHAFT SPEED (RPM)	CARTRIDGE SPEED (RPM)	PUMP BRG FLOW (LB/SEC)	LH2 DENSITY AT ORIF (PCF)	AVERAGE PAD PRESSURE (PSIA)	PUMP BRG PRESSURE RATIO
1	108.2	47.8	45.1	1445.	1905.	0.0719	1.6070	150.5	0.1595
2	106.4	48.5	45.2	27485.	27075.	0.0916	1.9760	188.5	0.2329
3	105.5	49.1	45.3	30866.	30865.	0.0986	2.1629	203.0	0.2517
4	104.6	49.3	45.4	31900.	32015.	0.1008	2.2185	207.2	0.2595
5	104.9	49.2	45.3	31633.	31693.	0.1020	2.2215	205.7	0.2554
6	107.6	49.8	46.5	32168.	32298.	0.1039	2.2743	210.4	0.2571
7	106.8	50.2	45.5	33897.	33920.	0.1019	2.3503	228.3	0.2897
8	106.5	49.6	45.5	31743.	31769.	0.1054	2.3463	207.6	0.2560
9	105.9	49.6	45.5	31993.	32107.	0.1086	2.3363	215.2	0.2589
10	105.4	49.3	45.4	33479.	33517.	0.1031	2.2312	224.4	0.2770
11	105.6	48.6	45.2	31322.	31360.	0.0995	2.1033	207.3	0.2522
12	107.3	49.1	45.3	32252.	32289.	0.0975	2.0249	215.0	0.2618
13	106.5	48.9	45.3	33262.	33241.	0.0954	2.0323	222.3	0.2805
14	109.5	110.0	53.0	14328.	13849.	0.0801	1.7217	164.9	0.1776
15	106.9	51.1	45.7	2967.	2931.	0.0725	1.6857	147.4	0.1586
16	67.4	34.7	42.7	1509.	1377.	0.0715	1.9184	112.8	0.1763
17	66.0	34.2	42.6	1114.	1021.	0.0723	2.1139	104.6	0.1599
18	49.4	28.5	41.3	119.	820.	0.0678	2.1237	93.0	0.1869
19	46.1	27.4	41.0	1.	461.	0.0614	2.0205	84.0	0.1770

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 7
TEST DATE 6-14-82

PROCESSING DATE 6-22-82
TEST DURATION, SEC 205.00

HYBRID BEARING DATA
PUMP - END (PAGE 3)

TIME SLICE NO	BRG DELTA P ORIFICE PSID	BRG DELTA P FILM PSID	BRG DELTA P TOTAL PSID	ORIFICE RESISTANCE SEC**2/ LB-IN**2	FLUID FILM RESISTANCE SEC**2/ LB-IN**2	POISEUILLE RENOLDS NO	COUETTE RENOLDS NO	LAMBDA BRG NO	TORQUE FLUID FILM (TEMP) IN-LBS
1	223.2	42.4	265.6	43178.4	8195.9	63303910.	702.	0.00014	-6.7732
2	270.4	82.1	352.5	32222.0	9781.4	72754162.	10030.	0.00185	2.2610
3	289.7	97.4	387.2	29796.6	10021.5	80069232.	11834.	0.00203	4.4652
4	292.9	102.6	395.6	28826.1	10100.4	81667904.	12397.	0.00209	5.2247
5	293.7	100.7	394.4	28203.4	9671.4	81790503.	12273.	0.00207	5.4094
6	297.0	102.8	399.8	27529.7	9528.7	84207833.	12816.	0.00209	6.2424
7	297.8	121.5	419.3	28664.2	11689.3	88916348.	13980.	0.00219	6.7126
8	294.1	101.2	395.2	26494.4	9114.9	85873290.	12835.	0.00205	8.2596
9	312.8	109.3	422.0	26526.4	9268.1	87909166.	12675.	0.00201	6.7508
10	310.4	118.9	429.3	29180.6	11181.5	85351710.	12975.	0.00213	3.8205
11	301.5	101.7	403.2	30459.0	10274.1	79276516.	11639.	0.00203	2.1369
12	303.7	107.7	411.3	31918.3	11319.1	77821739.	11805.	0.00210	-0.0788
13	297.2	115.8	413.0	32685.2	12741.5	78420620.	12353.	0.00218	0.1996
14	256.4	55.4	311.8	39981.6	8632.7	67894061.	4960.	0.00094	-75.0900
15	4.8	40.5	255.3	40896.0	7706.4	64512330.	1122.	0.00021	17.1635
16	212.0	45.4	257.4	41479.4	8875.7	54532637.	415.	0.00011	152.0791
17	202.6	38.5	241.1	38731.4	7369.8	52945255.	310.	0.00008	306.7248
18	189.4	43.5	232.9	41201.2	9473.5	45798278.	216.	0.00007	400.8969
19	175.9	37.8	213.7	46587.2	10016.5	40967489.	116.	0.00004	631.3694

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MK48-?
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 7
TEST DATE 6-14-82

PROCESSING DATE 6-22-82
TEST DURATION, SEC 205.00

HYBRID BEARING DATA
PUMP AND TURBINE END (PAGE 4)

	- - - PUMP - - -			- - - TURBINE - - -					
TIME SLICE NO	HS BRG CLEARANCE RADIAL IN	VISCOSITY PUMP BRG LB-HR/FT**2 * E10	CSUBP PUMP BRG BTU/ LB-R	HS BRG CLEARANCE RADIAL IN	VISCOSITY TURB BRG LB-HR/FT**2 * E10	CSUBP TURB BRG BTU/ LB-R	POISEUILLE RENOLDS NO	COUETTE RENOLDS NO	LAMBDA TURB NO
1	0.00245	0.13581	3.2706	0.00246	0.13998	4.8978	49541027.	2.	0.0000
2	0.00234	0.14350	3.4790	0.00246	0.18720	5.9511	95611946.	3.	0.0000
3	0.00231	0.14436	3.6131	0.00246	0.21588	5.4063	128537488.	7.	0.0000
4	0.00230	0.14477	3.6719	0.00245	0.22588	5.2039	137554784.	2622.	0.0003
5	0.00230	0.14449	3.6611	0.00245	0.23018	5.0700	147444175.	1630.	0.0002
6	0.00230	0.14507	3.7209	0.00246	0.24086	4.9241	148049278.	6.	0.0000
7	0.00228	0.14774	3.9191	0.00245	0.25182	4.6981	156474694.	2577.	0.0002
8	0.00230	0.14378	3.7801	0.00246	0.25424	4.6630	165161792.	4.	0.0000
9	0.00230	0.14618	3.7303	0.00246	0.26741	4.2713	211592905.	4.	0.0000
10	0.00229	0.14851	3.7031	0.00246	0.26559	4.2923	209984492.	4.	0.0000
11	0.00231	0.14643	3.5399	0.00246	0.24549	4.6092	183426237.	2.	0.0000
12	0.00230	0.14883	3.5085	0.00243	0.23875	4.6825	168628493.	6925.	0.0006
13	0.00229	0.14961	3.5729	0.00245	0.24109	4.6758	169680076.	3080.	0.0003
14	0.00242	0.14059	3.2778	0.00246	0.17930	5.5752	147610033.	4.	0.0000
15	0.00245	0.13306	3.3350	0.00246	0.14167	6.4833	69582016.	2.	0.0000
16	0.00246	0.12509	3.2161	0.00246	0.13185	8.4500	53695315.	1.	0.0000
17	0.00246	0.12180	3.2256	0.00246	0.12493	10.0882	48991614.	1.	0.0000
18	0.00246	0.11813	3.1649	0.00246	0.11990	10.3711	43874363.	2.	0.0000
19	0.00246	0.11515	3.1083	0.00246	0.11480	8.8885	37950309.	2.	0.0000

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 7
TEST DATE 6-14-82

PROCESSING DATE 6-22-82
TEST DURATION, SEC 205.00

H Y B R I D B E A R I N G D A T A
TURBINE END (PAGE 1)

TIME SLICE NO	TURB BRG SUPPLY U/S PRESS (PSIA)	TURB BRG SUPPLY U/S TEMP (DEG R)	TURB BRG SUPPLY D/S ORIF PRESS (PSIA)	TURB BRG SUPPLY ORIF DP (PSID)	TURB BRG SUPPLY MANIF PRESS (PSIA)	TURB BRG DISCH PRESS (PSIA)	TURB BRG SUMP PRESS (PSIA)	-- TURBINE BRG -- DISCHARGE PRESS (PSIA)	-- TURBINE BRG -- LINE TEMP (DEG R)
1	291.5	74.5	286.1	4.9	268.5	114.2	97.4	36.9	55.2
2	584.7	81.0	566.7	18.9	528.3	277.9	258.5	72.4	49.1
3	755.5	81.8	729.9	29.9	675.7	326.2	304.7	82.6	50.5
4	807.2	81.6	776.6	36.3	719.9	335.5	315.2	95.0	51.7
5	842.1	81.7	811.1	39.5	747.9	335.1	314.7	94.8	51.7
6	875.6	81.4	841.3	41.9	778.2	362.8	341.1	89.6	51.2
7	929.4	81.0	884.9	40.7	829.7	383.2	361.4	105.8	53.0
8	942.0	80.2	902.4	48.1	829.9	355.1	334.7	94.0	51.6
9	1118.9	82.0	1060.8	59.3	977.7	367.5	342.4	98.1	52.0
10	1132.7	84.0	1083.7	58.3	995.8	389.0	365.8	101.9	52.5
11	1007.6	84.8	966.5	52.5	888.3	356.2	334.3	89.4	51.2
12	981.1	86.7	943.3	45.9	873.9	369.3	346.9	89.6	51.2
13	980.9	86.4	943.4	44.0	872.6	378.0	356.2	102.1	52.5
14	660.0	83.4	635.7	27.5	588.4	183.5	160.2	114.7	55.6
15	341.2	73.0	331.2	7.7	309.8	118.7	101.3	42.6	47.7
16	258.1	66.2	252.7	2.7	237.8	79.3	66.4	29.2	42.1
17	227.0	63.4	222.9	0.7	211.7	77.1	64.0	28.3	41.8
18	199.5	61.0	196.5	0.0	185.7	58.8	47.7	24.4	40.9
19	179.1	59.5	176.4	0.0	165.5	54.8	43.8	24.2	40.7

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MK48-1
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

PAGE 7.11

RUN NUMBER 7
TEST DATE 6-14-82

PROCESSING DATE 6-22-82
TEST DURATION, SEC 205.00

H Y B R I D B E A R I N G D A T A
TURBINE END (PAGE 2)

TIME SLICE NO	SHAFT SPEED (RPM)	TURBINE CARTRIDGE SPEED (RPM)	TURBINE H/S BRG FLOW (LB/SEC)	LH2 DENSITY AT ORIF (PCF)	TURB BRG SUPPLY MANIF PRESS (PSIA)	TURB BRG DISCH PRESS (PSIA)	TURB BRG SUMP PRESS (PSIA)	HYDROSTATIC BEARING DELTA PRESS (PSID)
1	1445.	6.	0.0367	1.086	268.5	114.2	97.4	171.09
2	27485.	6.	0.1017	2.180	528.3	277.9	258.5	269.80
3	30866.	12.	0.1411	2.653	676.7	326.2	304.7	372.06
4	31900.	4970.	0.1591	2.781	718.9	335.5	315.2	403.73
5	31633.	2491.	0.1680	2.846	747.9	335.1	314.7	433.70
6	32168.	9.	0.1755	2.931	778.2	362.8	341.1	437.18
7	33097.	3633.	0.1764	3.043	829.7	383.2	361.4	468.26
8	31743.	6.	0.1935	3.103	829.9	356.1	334.7	495.14
9	31993.	6.	0.2201	3.255	977.7	367.5	342.4	635.26
10	33479.	6.	0.2159	3.184	995.8	389.0	365.8	630.07
11	31322.	3.	0.1979	2.973	888.3	356.2	334.3	553.94
12	32252.	10611.	0.1807	2.838	870.8	369.3	346.9	523.93
13	33262.	4641.	0.1774	2.853	872.6	378.0	356.2	516.40
14	14328.	9.	0.1254	2.283	588.4	180.5	160.2	428.29
15	2967.	6.	0.0538	1.502	309.8	118.7	101.3	208.47
16	1509.	3.	0.0309	1.420	237.8	79.3	66.4	171.44
17	1114.	3.	0.0161	1.393	211.7	77.1	64.0	147.78
18	119.	6.	0.0	1.311	185.7	58.6	47.7	138.01
19	1.	6.	0.0	1.117	165.5	54.8	43.8	121.71

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RUN NUMBER 8A
TEST DATE 6-16-82

PROCESSING DATE 6-21-82
TEST DURATION, SEC 201.00

COMMENTS . . .

TEST 016-008A
SLICES 1 THRU 30

AMBIENT PRESSURE		13.8000
LO2 VENTURI (GG) P/N V160248-SGR S/N L-71	UPSTREAM DIAMETER	0.0
	THROAT DIAMETER	0.0
	THROAT CD	0.0
GH2 VENTURI (TURB) P/N VP031200-SGR S/N 9731	UPSTREAM DIAMETER	2.3000
	THROAT DIAMETER	1.3085
	THROAT CD	0.9873
LH2 VENTURI (GG) P/N V320471-SGR S/N 8873	UPSTREAM DIAMETER	0.0
	THROAT DIAMETER	0.0
	THROAT CD	0.0
LH2 VENTURI (PUMP DISCH) P/N V320709-SGR S/N 8874	UPSTREAM DIAMETER	1.6890
	THROAT DIAMETER	0.7090
	THROAT CD	0.9760

TURBINE SYSTEM EFF. AREA 0.70470
TURBINE EXHAUST ORIFICE 4 EACH 0.31200
4 EACH 0.32500
1 EACH 0.30800

HYDROSTATIC BEARING SUPPLY SYSTEM
TURBINE INLET DUCT DIA 0.334 ORIFICE DIA 0.194
PUMP INLET DUCT DIA 0.402 ORIFICE DIA 0.175

ORIGINAL PAGE IS
OF POOR QUALITY

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 8A
TEST DATE 6-16-82

PROCESSING DATE 6-21-82
TEST DURATION, SEC 201.00

GASEOUS HYDROGEN TURBINE DRIVE PARAMETERS

TIME SLICE NO	BEGIN TIME (SEC)	END TIME (SEC)	REG U/S PR (PSIA)	VENTURI U/S PR (PSIA)	VENTURI U/S TEMP (DEG R)	VENTURI DELTA PR (PSID)	SPIN VALVE POSN	SPIN VALVE U/S PR (PSIA)	FAC DUCT PR (PSIA)	TURB GH2 FLOW (LB/SEC)	SPEED (RPM)
1	89.999	90.222	4958.1	4829.3	536.89	0.0	-1.13	4940.6	13.80	0.0023	2.
2	109.999	110.225	4932.5	4802.4	536.25	0.0	-1.13	4915.0	13.80	0.0022	1.
3	127.981	128.126	4926.1	4797.3	536.25	0.0	0.96	4907.7	13.80	0.0021	674.
4	128.971	129.157	4922.0	4791.8	533.12	0.14	3.79	4902.5	13.81	0.4285	27871.
5	129.961	130.146	4916.8	4786.2	533.77	0.29	4.74	4896.2	13.80	0.6213	27680.
6	130.992	131.136	4908.6	4777.9	534.47	0.47	5.73	4888.2	13.80	0.7935	32115.
7	131.982	132.126	4900.5	4770.5	534.85	0.43	5.52	4881.5	13.80	0.7528	31601.
8	132.972	133.157	4892.7	4761.7	535.13	0.40	5.41	4873.4	13.80	0.7310	31085.
9	133.962	134.147	4884.4	4754.5	535.40	0.43	5.53	4864.9	13.80	0.7546	31322.
10	139.983	140.251	4841.1	4712.4	536.40	0.38	5.28	4821.6	13.80	0.7106	30778.
11	149.964	150.233	4770.7	4640.6	537.57	0.33	5.22	4750.3	13.80	0.6568	31320.
12	159.987	160.255	4681.1	4552.5	538.40	0.39	5.39	4661.7	13.80	0.7114	31707.
13	169.988	170.236	4609.3	4479.6	538.80	0.32	5.09	4588.4	13.80	0.6440	30685.
14	170.999	171.143	4602.1	4472.9	538.64	0.31	5.09	4581.5	13.80	0.6271	30572.
15	171.989	172.133	4594.7	4465.6	538.74	0.33	5.09	4575.8	13.80	0.6460	30935.
16	172.979	173.123	4588.5	4458.9	538.81	0.35	5.36	4568.0	13.80	0.6644	31702.
17	173.969	174.154	4580.9	4451.8	538.89	0.39	5.53	4561.1	13.80	0.7047	32571.
18	174.959	175.144	4573.9	4444.2	538.97	0.39	5.53	4553.2	13.80	0.7042	32945.
19	175.990	176.134	4566.1	4436.9	539.17	0.39	5.42	4546.4	13.82	0.7041	32793.
20	179.990	180.258	4538.2	4408.9	539.12	0.33	5.24	4517.3	13.81	0.6500	31826.
21	189.972	190.240	4465.5	4336.7	539.52	0.40	5.60	4445.6	13.81	0.7079	32921.
22	199.994	200.221	4366.8	4238.5	539.71	0.33	5.37	4346.9	13.82	0.6393	32536.
23	209.975	210.243	4265.2	4136.7	539.86	0.33	5.40	4245.6	13.82	0.6352	32100.
24	213.976	214.120	4241.4	4112.3	539.83	0.83	7.61	4218.3	13.83	1.0004	36493.
25	214.966	215.151	4229.9	4099.0	539.92	2.72	12.71	4200.1	14.58	1.8067	46919.
26	215.997	216.141	4210.0	4079.6	540.14	4.65	16.31	4175.7	19.09	0.0	53091.
27	216.987	217.131	4189.4	4055.5	540.23	6.92	19.64	4146.4	23.99	0.0	57568.
28	217.977	218.121	4162.0	4025.9	540.27	10.32	23.84	4108.2	30.15	0.0	62318.

C-4

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 8A
TEST DATE 6-16-82

PROCESSING DATE 6-21-82
TEST DURATION, SE 201.00

H Y B R I D   B E A R I N G   D A T A
PUMP - END (PAGE 1)

TIME SLICE NO	PUMP BRG SUPPLY U/S PRESS (PSIA)	PUMP BRG SUPPLY TEMP (DEG R)	PUMP BRG SUPPLY D/S ORIF PRESS (PSIA)	PUMP BRG SUPPLY ORIF DP (PSID)	PUMP BRG SUPPLY MANIF PRESS (PSIA)	PUMP BRG PAD PRESSURES 3.00 OCLOCK (PSIA)	9.00 OCLOCK (PSIA)	6.30 OCLOCK (PSIA) Bad tap
1	104.0	53.0	111.7	0.0	120.1	110.2	108.5	13.4
2	379.9	90.6	364.9	19.9	375.4	150.0	142.2	13.6
3	373.4	83.0	362.6	16.1	373.2	227.7	224.9	12.5
4	467.7	85.3	448.1	23.4	459.0	255.8	251.8	13.0
5	469.8	84.8	450.1	23.2	461.3	270.3	267.2	12.9
6	509.7	84.8	487.2	24.7	498.3	300.2	298.3	12.8
7	512.0	84.3	491.8	24.1	502.6	310.3	307.7	12.4
8	509.6	83.7	489.1	23.7	501.4	310.3	306.2	12.3
9	510.2	83.5	489.0	24.6	501.2	302.6	298.9	12.1
10	506.1	80.1	482.6	27.2	493.4	268.5	262.9	11.9
11	526.6	79.5	498.4	31.1	509.7	258.5	252.3	11.8
12	525.1	76.6	497.7	30.4	509.1	256.9	252.1	11.8
13	540.0	76.2	510.1	31.9	521.5	257.8	258.2	11.7
14	661.0	78.0	617.8	4[illegible].7	629.9	286.4	284.8	11.8
15	802.0	79.2	743.7	58.7	[illegible]55.3	306.3	309.0	11.8
16	948.3	79.7	874.2	75.0	884.9	322.5	331.5	11.8
17	1094.1	79.9	1003.6	89.1	1015.1	342.2	351.7	11.8
18	1176.0	79.4	1077.1	97.3	1087.8	351.2	363.0	11.8
19	1192.5	79.3	1092.6	98.0	1103.2	355.2	365.3	11.9
20	1196.9	79.4	1094.9	99.6	1105.6	355.1	364.0	11.9
21	1201.9	75.4	1096.5	102.2	1106.6	336.1	352.7	11.9
22	1212.7	83.8	1115.4	94.4	1126.7	387.2	396.9	12.3
23	1184.3	93.3	1095.8	84.3	1108.0	396.9	406.4	12.6
24	1184.3	92.2	1095.5	84.1	1108.2	413.7	418.0	12.4
25	1184.8	92.0	1098.8	83.5	1109.9	432.1	431.3	12.7
26	1187.1	91.6	1099.7	84.5	1111.4	426.2	425.0	12.6
27	1188.3	91.3	1101.1	93.8	1112.9	427.4	428.8	12.3
28	11[illegible].5	90.8	1103.3	7[illegible].7	1114.6	469.0	472.0	12.4
29	1183.1	90.5	1108.2	69.7	1120.0	553.9	567.0	12.1
30	1176.5	90.1	1101.7	69.4	1114.5	556.7	569.0	12.8

ORIGINAL PAGE IS
OF POOR QUALITY

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 8A
TEST DATE 6-16-82

PROCESSING DATE 6-21-82
TEST DURATION, SEC 201.00

H Y B R I D B E A R I N G D A T A
PUMP - END (PAGE 2)

TIME SLICE NO	PUMP BRG SUMP PRESSURE (PSIA)	PUMP BRG SUMP OUT PRESSURE (PSIA)	PUMP BRG SUMP OUT TEMP (DEG R)	SHAFT SPEED (RPM)	CARTRIDGE SPEED (RPM)	PUMP BRG FLOW (LB/SEC)	LH2 DENSITY AT ORIF (PCF)	AVERAGE PAD PRESSURE (PSIA)	PUMP BRG PRESSURE RATIO
1	107.3	51.4	42.9	2.	2.	0.0	0.5525	109.3	0.1567
2	111.2	48.2	44.7	1.	14.	0.0499	0.9846	146.1	0.1322
3	110.4	48.2	44.7	674.	723.	0.0487	1.1588	226.3	0.4412
4	109.0	48.8	44.8	27871.	7561.	0.0657	1.4538	253.8	0.4136
5	107.7	47.9	44.6	27680.	15658.	0.0661	1.4865	288.8	0.4555
6	107.5	49.8	44.8	32115.	23856.	0.0718	1.6437	298.2	0.4881
7	107.4	49.6	44.8	31601.	29414.	0.0717	1.6807	309.0	0.5101
8	108.7	48.8	44.9	31085.	31083.	0.0716	1.7025	308.3	0.5082
9	109.9	49.1	44.9	31372.	31331.	0.0732	1.7170	300.7	0.4877
10	107.2	48.8	44.9	30778.	30770.	0.0813	1.9118	265.7	0.4105
11	109.9	50.9	45.2	31320.	31349.	0.0971	2.3926	255.4	0.3638
12	109.7	51.1	45.2	31707.	31774.	0.0944	2.3045	254.5	0.3624
13	109.8	51.0	45.7	30685.	30694.	0.0983	2.3862	258.0	0.3601
14	110.9	50.9	45.2	30577.	30595.	0.1214	2.6580	285.6	0.3366
15	110.7	50.6	45.1	30935.	30927.	0.1474	2.9143	307.6	0.3055
16	110.6	50.3	45.0	31707.	31764.	0.1729	3.1405	327.0	0.2795
17	110.7	50.2	45.0	32571.	32614.	0.1939	3.3240	346.9	0.2612
18	111.0	50.2	45.0	32945.	32968.	0.2061	3.4357	357.1	0.2519
19	112.2	50.6	45.2	32793.	32747.	0.2074	3.4546	360.2	0.2503
20	112.5	50.0	45.0	31826.	31761.	0.2104	3.4993	359.5	0.2487
21	112.7	50.4	45.1	32921.	32913.	0.2171	3.6292	344.4	0.2331
22	113.8	50.4	45.1	32536.	32535.	0.1986	3.2889	392.1	0.2747
23	113.0	50.2	56.1	32100.	12112.	0.1748	2.8558	401.7	0.2901
24	111.0	50.4	45.1	36493.	36609.	0.1760	2.8987	415.9	0.3057
25	109.9	52.2	45.4	46919.	39850.	0.1756	2.9095	431.7	0.3218
26	110.4	54.5	45.8	53091.	37045.	0.1772	2.9273	425.6	0.3148
27	111.3	56.5	46.2	67568.	38202.	0.1769	2.9421	428.1	.3163
28	109.8	58.3	46.4	62318.	40164.	0.1730	2.9571	470.5	0.3590
29	108.0	60.1	46.7	65075.	63790.	0.1620	2.9682	540.5	0.4471
30	107.6	60.9	45.8	64687.	64111.	0.1628	2.9777	562.8	0.4522

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

PAGE 8. 8

RUN NUMBER 8A
TEST DATE 6-16-82

PROCESSING DATE 6-21-82
TEST DURATION, SEC 201.00

HYBRID BEARING DATA
PUMP - END (PAGE 3)

TIME SLICE NO	BRG DELTA P ORIFICE PSID	BRG DELTA P FILM PSID	BRG DELTA P TOTAL PSID	ORIFICE RESISTANCE SEC**2/ LB-IN**2	FLUID FILM RESISTANCE SEC**2/ LB-IN**2	POISEUILLE RENOLDS NO	COUETTE RENOLDS NO	LAMBDA BRG NO	TORQUE FLUID FILM (TEMP) IN-LBS
1	10.8	2.0	12.8	******************	******************	7774778.	1.	0.00000	0.0
2	229.3	34.9	264.2	92036.1	14020.3	38051387.	4.	0.00000	**********
3	146.8	115.9	262.8	61941.0	48904.6	57959870.	277.	0.00006	-1325.6039
4	205.3	144.8	350.1	47524.7	33575.5	74031976.	2904.	0.00052	-165.7259
5	192.6	161.1	353.7	44032.9	36829.1	74320452.	6192.	0.00111	-79.5375
6	200.0	190.7	390.7	38802.1	38999.7	80480184.	9848.	0.00187	-54.8480
7	193.6	201.6	395.2	37610.3	39163.0	78422808.	12266.	0.00215	-43.5325
8	193.2	199.6	392.8	37668.6	38918.1	77724474.	13066.	0.00230	-40.4982
9	200.4	190.8	391.3	37420.7	35629.6	77653425.	13104.	0.00230	-40.8067
10	227.6	158.5	386.2	34453.5	23994.4	80677253.	12874.	0.00218	-41.9122
11	254.4	145.4	399.8	26951.5	15411.9	93349323.	14400.	0.00211	-39.7274
12	254.8	144.7	399.4	28988.9	18251.3	90654108.	14210.	0.00215	-39.7389
13	263.5	148.3	411.8	27266.1	15347.1	95162766.	13960.	0.00202	-41.7691
14	344.3	174.7	519.0	23351.2	11847.4	117198734.	14115.	0.00173	-50.6299
15	447.7	197.0	644.6	20606.1	9065.6	140384975.	14299.	0.00152	-59.4606
16	557.8	216.4	774.3	18663.4	7240.3	164404649.	14859.	0.00138	-66.4850
17	668.1	236.2	904.3	17768.0	6282.3	188438790.	15533.	0.00128	-71.6685
18	730.7	246.1	976.8	17208.6	5794.0	202643073.	15990.	0.00124	-73.8928
19	743.0	248.1	991.1	17274.7	5767.9	206538274.	16014.	0.00122	-74.4487
20	746.0	247.0	993.0	16859.7	5582.0	210798657.	15820.	0.00118	-75.9730
21	762.2	231.7	993.9	16176.1	4917.3	209524840.	16679.	0.00125	-68.8309
22	734.6	278.2	1012.9	18633.6	7057.5	200486344.	15393.	0.00120	-81.3663
23	706.4	288.7	995.1	23114.2	9447.1	170433289.	13077.	0.00120	-6.4525
24	692.5	304.8	997.2	22356.9	9843.7	184725781.	15144.	0.00148	-79.0710
25	678.2	321.8	1000.0	21989.8	10435.5	159294484.	16564.	0.00163	-71.8159
26	685.8	315.2	1001.0	21841.4	10036.7	166592799.	15591.	0.00147	-76.7326
27	684.8	316.8	1001.6	21876.7	10120.5	165205624.	16150.	0.00153	-73.2136
28	64[illegible].1	360.7	1004.9	21517.9	12056.[illegible]	141516272.	20278.	0.00225	-56.[illegible]1
29	559.5	452.5	1012.0	21302.7	17233.3	98610628.	25787.	0.00412	-38.9664
30	551.7	455.5	1007.2	21022.4	17354.5	97339944.	25998.	0.00421	-38.2607

Jackson

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 8A
TEST DATE 6-15-82

PROCESSING DATE 6-21-82
TEST DURATION, SEC 201.00

H Y B R I D   B E A R I N G   D A T A
PUMP AND TURBINE END (PAGE 4)

	- - - PUMP - - -			- - - TURBINE - - -					
TIME SLICE NO	HS BRG CLEARANCE RADIAL IN	VISCOSITY PUMP BRG LB-HR/FT**2 * E10	CSUMP PUMP BRG BTU/ LB-R	HS BRG CLEARANCE RADIAL IN	VISCOSITY TURB BRG LB-HR/FT**2 * E10	CSUMP TURB BRG BTU/ LB-R	POISEUILLE RENOLDS NO	COUETTE RENOLDS NO	LAMBDA TURB NO
1	0.00246	0.10803	5.6636	0.00246	0.20397	2.8778	89324.	0.	0.0000
2	0.00246	0.15365	2.8895	0.00246	0.16611	3.1688	25636965.	1.	0.0000
3	0.00246	0.15265	3.4522	0.00246	0.15278	3.5777	36063867.	0.	0.0000
4	0.00244	0.15815	3.5096	0.00246	0.17999	4.3827	71037715.	134.	0.0000
5	0.00241	0.15975	3.6347	0.00246	0.18356	4.5996	87130272.	68.	0.0000
6	0.00236	0.16347	3.8350	0.00246	0.19886	4.7656	108591607.	416.	0.0000
7	0.00232	0.16535	3.9559	0.00246	0.20361	4.7893	124554110.	510.	0.0001
8	0.00231	0.16511	4.0036	0.00246	0.20581	4.8083	134047186.	139.	0.0000
9	0.00231	0.16352	3.9636	0.00245	0.20813	4.8111	138658626.	861.	0.0001
10	0.00231	0.15604	3.9719	0.00246	0.21342	5.0289	145934825.	61.	0.0000
11	0.00231	0.15264	4.4441	0.00246	0.25406	4.6721	163814878.	5.	0.0000
12	0.00230	0.15264	4.2900	0.00246	0.24961	4.7014	164905048.	8.	0.0000
13	0.00231	0.15341	4.3704	0.00246	0.24807	4.7330	164942845.	379.	0.0000
14	0.00231	0.15938	4.4682	0.00246	0.26065	4.4131	196446249.	83.	0.0000
15	0.00231	0.16522	4.5577	0.00245	0.27983	4.0724	237835131.	3058.	0.0002
16	0.00230	0.17036	4.7215	0.00246	0.31438	3.7136	288705759.	-15.	-0.0000
17	0.00229	0.17559	4.9339	0.00246	0.34487	3.4928	322270308.	-5.	-0.0000
18	0.00229	0.17910	5.1671	0.00246	0.36771	3.3480	344986786.	6.	0.0000
19	0.00229	0.18007	5.2188	0.00246	0.37733	3.2972	354009903.	12.	0.0000
20	0.00230	0.18146	5.4529	0.00246	0.38876	3.2360	356671307.	1.	0.0000
21	0.00229	0.18423	6.2102	0.00246	0.41707	3.1765	334760746.	1.	0.0000
22	0.00229	0.19374	4.7047	0.00246	0.42580	3.0239	449438090.	7.	0.0000
23	0.00230	0.18336	3.8353	0.00246	0.31193	3.5163	430333099.	3.	0.0000
24	0.00226	0.18548	3.9672	0.00246	0.33308	3.4179	434652523.	5.	0.0000
25	0.00222	0.18807	4.0578	0.00246	0.38019	3.2388	422961681.	6.	0.0000
26	0.00225	0.18712	4.0566	0.00246	0.43575	3.0479	470383816.	14.	0.0000
27	0.00224	0.19765	4.0935	0.00246	0.47823	2.9273	405371378.	6.	0.0000
28	0.00212	0.19621	4.3232	0.00246	0.50044	2.8874	369011432.	6.	0.0000
29	0.00189	0.21639	4.7076	0.00246	0.50593	2.8882	343159970.	8.	0.0000

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OF POOR QUALITY

RUN NUMBER 8A
TEST DATE 6-16-82

PROCESSING DATE 6-21-82
TEST DURATION, SEC 201.00

H Y B R I D B E A R I N G D A T A
TURBINE END (PAGE 1)

TIME SLICE NO	TURB BRG SUPPLY U/S PRESS (PSIA)	TURB BRG SUPPLY U/S TEMP (DEG R)	TURB BRG SUPPLY D/S ORIF PRESS (PSIA)	TURB BRG SUPPLY ORIF DP (PSID)	TURB BRG SUPPLY MANIF PRESS (PSIA)	TURB BRG DISCH PRESS (PSIA)	TURB BRG SUMP PRESS (PSIA)	-- TURBINE BRG -- DISCHARGE LINE PRESS (PSIA)	-- TURBINE BRG -- DISCHARGE LINE TEMP (DEG R)
1	89.5	137.6	88.4	0.0	89.8	101.4	87.0	40.6	43.4
2	297.7	99.0	280.3	11.0	275.0	117.8	99.7	39.0	89.3
3	299.3	86.6	289.8	10.9	276.1	117.8	99.5	39.2	73.5
4	546.0	91.7	529.3	23.8	501.1	286.6	265.0	81.3	49.9
5	599.2	91.1	577.4	28.3	544.1	285.0	263.8	76.2	49.1
6	722.8	91.7	695.8	34.9	653.9	342.5	320.0	92.6	51.0
7	777.8	91.7	746.9	38.7	699.9	342.9	320.0	88.8	50.7
8	804.4	91.4	771.8	40.5	722.0	337.8	315.5	88.5	50.6
9	822.8	91.2	789.6	42.4	738.4	341.6	318.3	91.7	50.9
10	825.0	87.1	792.9	42.0	739.5	333.7	310.8	86.8	50.4
11	947.0	80.3	898.6	52.2	878.4	359.5	337.5	97.7	51.6
12	948.5	81.9	908.8	52.0	838.1	367.3	343.8	99.2	51.8
13	924.8	80.7	885.6	49.6	818.0	350.5	327.2	103.2	51.9
14	1044.9	81.2	995.5	60.1	914.8	356.7	331.7	97.3	51.6
15	1197.2	80.9	1140.1	69.4	1042.8	362.0	336.0	106.1	52.5
16	1425.9	80.0	1351.5	88.7	1228.7	384.2	355.2	106.5	52.5
17	1619.2	79.1	1532.1	103.8	1390.8	404.9	373.1	110.8	53.0
18	1755.0	77.9	1661.4	111.0	1505.0	414.9	383.9	113.2	53.2
19	1815.4	77.3	1717.7	116.4	1553.4	416.3	384.9	114.3	53.4
20	1835.1	75.9	1739.5	113.9	1572.4	404.9	373.4	111.8	53.1
21	1828.6	72.2	1732.0	113.7	1563.0	415.0	304.6	119.8	53.9
22	2429.7	78.2	2298.8	156.5	2080.0	450.3	413.3	123.7	54.3
23	2004.0	93.0	1902.6	124.3	1739.4	427.9	392.6	121.7	57.6
24	2132.0	91.4	2021.0	132.0	1845.1	491.7	455.8	137.0	58.1
25	2436.2	89.4	2313.3	147.3	2110.6	687.3	652.3	186.1	62.3
26	2825.1	86.1	2678.2	174.9	2447.1	840.2	807.1	228.2	65.8
27	[illegible]91.9	83.3	2931.9	192.5	2672.8	962.1	929.9	258.4	68.0
28	3154.2	82.0	2993.9	193.0	2736.6	1090.4	1061.2	289.0	69.8
29	3111.7	81.9	2960.9	182.6	2714.2	1160.6	1134.6	308.4	71.0
30	3080.4	81.5	2916.5	173.2	2673.0	1132.8	1107.9	317.3	71.1

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MK48-F

LIQUID HYDROGEN TURBOPUMP ASSEMBLY

PAGE 8.11

RUN NUMBER 8 A
TEST DATE 6-16-82

PROCESSING DATE 6-21-82
TEST DURATION, SEC 201.00

H Y B R I D   B E A R I N G   D A T A
TURBINE END (PAGE 2)

TIME SLICE NO	SHAFT SPEED (RPM)	TURBINE CARTRIDGE SPEED (RPM)	TURBINE H/S BRG FLOW (LB/SEC)	LH2 DENSITY AT ORIF (PCF)	TURB BRG SUPPLY MANIF PRESS (PSIA)	TURB BRG DISCH PRESS (PSIA)	TURB BRG SUMP PRESS (PSIA)	HYDROSTATIC BEARING DELTA PRESS (PSID)
1	2.	5.	0.0	0.123	89.8	101.9	87.0	2.84
2	1.	7.	0.0420	0.639	275.0	117.8	99.7	175.28
3	674.	0.	0.0468	0.798	276.1	117.8	99.5	176.59
4	27871.	296.	0.0942	1.487	501.1	286.6	265.0	236.11
5	27690.	143.	0.1092	1.679	544.1	285.0	263.8	280.25
6	32115.	772.	0.1328	2.015	653.9	342.5	320.0	333.91
7	31601.	916.	0.1448	2.160	699.9	342.9	370.0	379.87
8	31085.	246.	0.1510	2.241	722.0	337.8	315.5	406.57
9	31322.	1503.	0.1562	2.293	738.4	341.6	318.3	420.10
10	30778.	101.	0.1625	2.507	739.5	333.7	310.8	428.67
11	31370.	7.	0.2016	3.100	829.4	359.5	337.5	490.87
12	31707.	11.	0.1987	3.025	838.1	367.3	343.8	494.28
13	30685.	546.	0.1948	3.049	818.0	350.5	327.2	490.78
14	30572.	114.	0.2197	3.202	914.8	356.7	331.7	583.10
15	30935.	3880.	0.2432	3.393	1042.0	362.0	336.0	706.72
16	31702.	-18.	0.2846	3.640	1228.7	384.2	355.2	873.45
17	32571.	-5.	0.3151	3.810	1390.8	404.9	373.1	1017.69
18	32945.	7.	0.3312	3.937	1505.0	414.9	383.9	1121.03
19	32793.	12.	0.3415	3.990	1553.4	416.3	384.9	1168.44
20	31825.	1.	0.3401	4.044	1572.4	404.9	373.4	1199.01
21	32921.	1.	0.3442	4.153	1563.0	415.0	384.6	1178.45
22	32536.	7.	0.4090	4.257	2080.0	450.3	413.3	1666.68
23	32100.	4.	0.3364	3.627	1739.4	477.9	392.6	1346.76
24	36493.	6.	0.3527	3.753	1865.1	491.7	455.8	1389.28
25	46919.	9.	0.3831	3.969	2110.6	687.3	652.3	1458.31
26	53091.	15.	0.4305	4.222	2442.1	840.2	807.1	1635.01
27	57568.	6.	0.4603	4.386	2672.	962.1	929.9	1742.58
28	62318.	6.	0.4645	4.436	2736.4	1090.4	1061.2	1675.45
29	65075.	9.	0.4505	4.428	2714.2	1160.6	1134.6	1579.61
30	64687.	141.	0.4387	4.416	2673.0	1132.9	1107.9	1565.11

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RUN NUMBER 86
TEST DATE 6-16-82

PROCESSING DATE 6-22-82
TEST DURATION, SEC 201.00

COMMENTS . . .

TEST 016-008B
SLICE 31 THRU 55

AMBIENT PRESSURE		13.8000
LO2 VENTURI (GG) P/N V160240-SGR S/N 8871	UPSTREAM DIAMETER	0.0
	THROAT DIAMETER	0.0
	THROAT CD	0.0
GH2 VENTURI (TURB) P/N VP031200-SGR S/N 9731	UPSTREAM DIAMETER	2.3000
	THROAT DIAMETER	1.3085
	THROAT CD	0.9873
LH2 VENTURI (GG) P/N V320471-SGR S/N 8873	UPSTREAM DIAMETER	0.0
	THROAT DIAMETER	0.0
	THROAT CD	0.0
LH2 VENTURI (PUMP DISCH) P/N V320709-SGR S/N 8874	UPSTREAM DIAMETER	1.6890
	THROAT DIAMETER	0.7090
	THROAT CD	0.9760
	TURBINE SYSTEM EFF. AREA	0.70470
	TURBINE EXHAUST ORIFICE 4 EACH	0.31200
	4 EACH	0.32500
	1 EACH	0.30800

HYDROSTATIC BEARING SUPPLY SYSTEM

TURBINE INLET DUCT DIA 0.334	ORIFICE DIA	0.194
PUMP INLET DUCT DIA 0.402	ORIFICE DIA	0.175

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OF POOR QUALITY

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 8B
TEST DATE 6-16-82

PROCESSING DATE 6-22-82
TEST DURATION, SEC 201.00

G A S E O U S   H Y D R O G E N   T U R B I N E   D R I V E   P A R A M E T E R S

TIME SLICE NO	BEGIN TIME (SEC)	END TIME (SEC)	REG U/S PR (PSIA)	VENTURI U/S PR (PSIA)	VENTURI U/S TEMP (DEG R)	VENTURI DELTA PR (PSID)	SPIN VALVE POSN	SPIN VALVE J/S PR (PSIA)	FAC DUCT PR (PSIA)	TURB GH2 FLOW (LB/SEC)	SPEED (RPM)
1	224.988	225.256	3945.4	3808.6	538.34	12.76	27.20	3883.1	33.37	3.7699	64501.
2	229.979	230.247	3795.8	3659.8	536.73	13.24	28.25	3732.0	33.35	3.7652	62757.
3	234.969	235.237	3658.1	3513.1	535.08	13.38	29.02	3585.8	33.02	3.7101	62312.
4	239.960	240.228	3507.2	3369.7	533.17	14.05	30.32	3440.4	33.22	3.7235	62324.
5	244.992	245.260	3365.8	3229.5	531.17	14.64	31.66	3296.8	33.29	3.7207	62274.
6	249.982	250.250	3229.8	3092.1	528.85	15.12	32.81	3159.6	33.17	3.6999	62820.
7	254.973	255.241	3095.9	2958.7	526.39	15.78	34.30	3023.5	33.23	3.6974	61975.
8	256.994	257.138	3046.0	2910.3	525.37	13.96	32.52	2979.8	30.74	3.4509	60437.
9	258.974	259.159	3081.1	2867.7	524.80	11.17	29.65	2944.0	26.94	3.0665	57666.
10	260.994	261.139	2962.3	2828.5	524.23	9.69	27.54	2909.7	24.61	2.8261	55641.
11	262.974	263.160	2926.4	2794.8	523.81	7.36	24.38	2881.8	21.16	2.4984	52996.
12	264.995	265.160	2895.6	2766.5	523.68	5.57	21.68	2858.1	18.11	2.1323	49554.
13	266.975	267.119	2869.9	2740.1	523.47	5.74	20.81	2832.4	17.14	2.0394	48455.
14	268.996	269.140	2842.4	2713.0	523.15	5.54	21.60	2803.9	17.79	2.1065	48907.
15	270.976	271.120	2815.7	2685.9	522.66	5.59	21.79	2777.7	17.81	2.1058	49868.
16	272.997	273.141	2788.6	2658.9	522.25	5.58	21.66	2751.0	17.51	2.0794	48620.
17	274.976	275.121	2762.7	2632.8	521.73	5.41	21.66	2725.3	17.26	2.0520	48400.
18	276.997	277.162	2735.6	2607.1	521.18	5.48	21.96	2698.2	17.38	2.0567	48449.
19	278.977	279.121	2709.3	2579.8	520.46	5.81	22.62	2671.7	17.86	2.1053	48961.
20	280.957	281.142	2682.5	2553.2	519.89	5.75	22.62	2645.7	17.71	2.0840	48682.
21	282.978	283.122	2668.2	2544.0	519.23	1.33	7.32	2646.0	14.20	1.0006	42804.
22	284.958	285.143	2663.1	2538.1	520.74	0.0	-1.13	359.4	14.01	0.0005	4307.
23	286.978	287.123	2649.9	2545.1	521.58	0.0	-1.13	69.8	14.02	0.0005	1872.
24	288.958	289.144	2672.1	2567.6	522.13	0.0	-1.16	16.6	14.04	0.0005	1358.
25	290.979	291.124	2676.9	2551.9	522.46	0.0	-1.13	13.6	14.07	0.0005	1012.

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 8B
TEST DATE 6-16-82

PROCESSING DATE 6-22-82
TEST DURATION, SEC 201.00

HYBRID BEARING DATA
PUMP - END (PAGE 1)

TIME SLICE NO	PUMP BRG SUPPLY U/S PRESS (PSIA)	PUMP BRG SUPPLY TEMP (DEG R)	PUMP BRG SUPPLY D/S ORIF PRESS (PSIA)	PUMP BRG SUPPLY ORIF DP (PSID)	PUMP BRG SUPPLY MANIF PRESS (PSIA)	--- PUMP BRG PAD PRESSURES --- 3.00 OCLOCK (PSIA)	9.00 OCLOCK (PSIA)	6.30 OCLOCK (PSIA)
1	1175.6	87.6	1100.1	72.1	1112.5	552.5	564.5	13.0
2	1176.1	85.2	1090.8	73.8	1110.4	535.9	546.7	12.7
3	1179.7	83.2	1099.7	76.9	1111.4	524.0	534.3	12.2
4	1170.0	81.3	1097.5	77.3	1109.2	520.6	532.9	12.7
5	1173.6	79.6	1093.3	76.4	1105.3	515.4	529.5	12.5
6	1172.5	77.9	1091.7	76.2	1103.9	509.8	526.4	12.2
7	1174.8	76.4	1090.8	76.0	1102.0	500.7	519.2	12.0
8	1173.0	75.8	1086.8	78.7	1098.5	484.0	496.0	12.5
9	1158.4	75.4	1070.8	80.5	1081.6	455.9	466.6	12.1
10	1130.6	74.8	1043.0	80.1	1054.0	433.8	442.0	12.2
11	1085.1	74.4	1000.4	79.8	1011.2	405.2	413.7	12.5
12	1039.4	74.0	957.7	77.2	968.1	379.6	384.1	12.6
13	1017.9	73.6	937.9	75.8	949.2	369.0	374.7	12.2
14	1025.5	73.0	944.1	77.1	954.8	371.6	376.5	12.2
15	1027.7	72.6	945.2	77.4	957.7	369.8	376.1	12.0
16	1022.3	72.1	939.8	76.9	951.0	363.9	366.8	12.2
17	1015.2	71.7	933.7	76.6	945.0	358.5	362.2	12.2
18	1015.8	71.2	934.5	76.9	945.4	356.3	359.0	12.0
19	1028.4	70.8	944.4	78.1	955.6	357.4	361.5	12.0
20	1022.6	70.3	939.4	76.5	950.7	351.2	355.9	12.2
21	997.0	69.9	919.1	75.3	928.4	330.6	334.0	12.3
22	564.0	65.6	525.8	37.2	535.9	191.6	190.7	12.8
23	210.6	58.9	212.1	0.0	222.0	107.7	105.0	13.0
24	142.3	56.9	147.7	0.0	157.2	63.5	58.8	16.3
25	139.5	56.6	144.4	0.0	153.8	60.2	55.7	15.4

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 85
TEST DATE 6-16-82

PROCESSING DATE 6-22-82
TEST DURATION, SEC 201.00

H Y B R I D   B E A R I N G   D A T A
PUMP - END (PAGE 2)

TIME SLICE NO	PUMP BRG SUMP PRESSURE (PSIA)	PUMP BRG SUMP OUT PRESSURE (PSIA)	PUMP BRG SUMP OUT TEMP (DEG R)	SHAFT SPEED (RPM)	CARTRIDGE SPEED (RPM)	PUMP BRG FLOW (LB/SEC)	LH2 DENSITY AT ORIF (PCF)	AVERAGE PAD PRESSURE (PSIA)	PUMP BRG PRESSURE RATIO
1	107.7	61.1	46.9	64581.	64005.	0.1680	3.0817	558.5	0.4486
2	106.1	59.6	46.6	62757.	62777.	0.1720	3.1846	541.3	0.4333
3	107.6	59.6	46.6	62312.	62347.	0.1788	3.2754	529.1	0.4199
4	105.3	59.1	46.6	62324.	62338.	0.1815	3.3571	526.8	0.4190
5	106.7	58.5	46.5	62274.	62203.	0.1823	3.4224	522.5	0.4164
6	105.1	58.7	46.5	62020.	62023.	0.1839	3.4951	518.1	0.4135
7	105.8	58.9	46.6	61975.	61961.	0.1854	3.5613	508.0	0.4037
8	105.3	58.1	46.4	60437.	60391.	0.1892	3.5842	490.0	0.3874
9	106.9	55.1	46.0	57666.	57660.	0.1916	3.5902	461.2	0.3635
10	107.9	55.5	46.0	55641.	55629.	0.1912	3.5874	437.9	0.3488
11	107.8	53.8	45.7	52596.	52521.	0.1900	3.5613	409.4	0.3339
12	107.5	52.3	45.6	49554.	49505.	0.1861	3.5327	381.9	0.3188
13	106.5	51.7	45.3	48455.	48432.	0.1843	3.5278	371.8	0.3149
14	109.3	52.5	45.6	48987.	48974.	0.1868	3.5622	374.1	0.3131
15	108.5	52.2	45.5	49068.	49029.	0.1877	3.5834	372.9	0.3114
16	107.6	53.4	45.7	48620.	48646.	0.1876	3.6023	365.4	0.3056
17	107.2	52.8	45.6	48400.	48429.	0.1874	3.6123	360.4	0.3022
18	107.7	52.0	45.4	48449.	48450.	0.1884	3.6353	357.6	0.2984
19	108.7	52.4	45.6	48961.	48944.	0.1907	3.6653	359.5	0.2961
20	107.7	53.4	45.6	48682.	48684.	0.1916	3.6828	353.6	0.2916
21	114.1	73.8	47.5	42804.	42262.	0.1875	3.6743	332.7	0.2685
22	109.5	51.9	45.5	4307.	14363.	0.1261	3.3617	191.2	0.1915
23	96.2	46.6	44.6	1872.	4699.	0.0	2.9715	106.4	0.0805
24	50.8	31.3	41.4	1358.	1350.	0.0	0.7937	61.2	0.0970
25	43.2	28.7	40.8	1012.	974.	0.0	0.7787	57.9	0.1331

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 8B
TEST DATE 5-16-82

PROCESSING DATE 6-22-82
TEST DURATION, SEC 201.00

H Y B R I D   B E A R I N G   D A T A
PUMP - END (PAGE 3)

TIME SLICE NO	BRG DELTA P ORIFICE PSID	BRG DELTA P FILM PSID	BRG DELTA P TOTAL PSID	ORIFICE RESISTANCE SEC**2/ LB-IN**2	FLUID FILM RESISTANCE SEC**2/ LB-IN**2	POISEUILLE RENOLDS NO	COUETTE RENOLDS NO	LAMBDA BRG NO	TORQUE FLUID FILM (TEMP) IN-LBS
1	554.0	450.8	1004.8	19624.9	15966.4	98661275.	26735.	0.00427	-37.2333
2	559.1	435.2	1004.2	19957.4	14573.5	102845895.	26877.	0.00412	-36.9178
3	582.3	421.6	1003.9	18205.2	13180.0	104447008.	27222.	0.00411	-36.3882
4	582.4	421.4	1003.9	17680.4	12792.8	103489194.	27663.	0.00422	-34.9448
5	582.8	415.8	998.6	17563.2	12514.6	101703834.	28022.	0.00434	-33.5030
6	585.8	413.0	998.8	17323.4	12213.8	130589835.	28292.	0.00444	-32.1459
7	594.0	402.2	996.2	17286.9	11703.6	98772522.	28456.	0.00454	-30.8806
8	608.4	384.7	993.2	16995.1	10746.6	102772135.	27816.	0.00427	-31.8609
9	620.4	354.4	974.7	16903.1	9655.1	110229905.	26742.	0.00382	-33.7366
10	616.1	330.0	946.1	16880.4	9041.7	114222697.	25952.	0.00356	-34.2349
11	601.8	301.7	903.5	16671.7	8356.3	121158674.	24742.	0.00318	-35.8454
12	586.3	274.4	860.6	16922.5	7919.0	128226078.	23551.	0.00285	-36.9177
13	577.3	265.3	842.6	17000.0	7812.1	129099520.	23058.	0.00277	-37.1220
14	580.8	264.7	845.5	16644.2	7587.1	125891764.	23420.	0.00287	-36.1912
15	584.8	264.5	849.3	16596.2	7505.0	124429444.	23360.	0.00290	-35.7964
16	585.6	257.8	843.3	16643.4	7326.1	123978887.	23110.	0.00288	-35.2197
17	584.6	253.2	837.8	16638.9	7205.4	123642822.	22993.	0.00288	-34.9654
18	587.8	250.0	837.8	16558.2	7042.4	123032996.	23076.	0.00290	-34.6270
19	596.1	250.8	846.9	16390.1	6895.7	121847396.	23394.	0.00297	-34.0321
20	597.2	245.8	843.0	16259.7	6693.2	122278507.	23319.	0.00295	-33.6002
21	595.7	218.7	814.4	16948.4	6221.4	141251355.	21353.	0.00231	-34.7241
22	344.7	81.6	426.4	21689.3	5137.1	148385534.	7928.	0.00074	-62.9333
23	115.6	10.1	125.8	************	************	56095312.	2254.	0.00048	0.0
24	96.0	10.3	106.4	************	************	24841709.	370.	0.00018	0.0
25	95.9	14.7	110.6	************	************	23488611.	241.	0.00013	0.0

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 8B
TEST DATE 6-16-82

PROCESSING DATE 6-22-82
TEST DURATION, SEC 201.00

H Y B R I D B E A R I N G D A T A
PUMP AND TURBINE END (PAGE 4)

TIME SLICE NO	PUMP: HS BRG CLEARANCE RADIAL IN	PUMP: VISCOSITY PUMP BRG LB-HR/FT**2 * E10	PUMP: CSUBP PUMP BRG BTU/ LB-R	TURBINE: HS BRG CLEARANCE RADIAL IN	TURBINE: VISCOSITY TURB BRG LB-HR/FT**2 * E10	TURBINE: CSUBP TURB BRG BTU/ LB-R	TURBINE: POISEUILLE RENOLDS NO	TURBINE: COUETTE RENOLDS NO	TURBINE: LAMBDA TURB NO
1	0.00189	0.22103	5.0376	0.00246	0.50344	2.9152	308996825.	8.	0.0000
2	0.00191	0.22197	5.3177	0.00246	0.49363	2.9413	292159819.	10.	0.0000
3	0.00191	0.22450	5.6014	0.002 6	0.49141	2.9659	265046958.	7.	0.0000
4	0.00191	0.23031	5.9215	0.00246	0.49335	2.9985	239404854.	4.	0.0000
5	0.00192	0.23659	6.1899	0.00246	0.48984	3.0134	211681576.	9.	0.0000
6	0.00192	0.24365	6.4515	0.00246	0.48536	3.0373	197178159.	7.	0.0000
7	0.00192	0.24924	6.6785	0.00246	0.48300	3.0613	179106225.	2.	0.0000
8	0.00195	0.24308	6.8808	0.00246	0.47839	3.0749	179728597.	26.	0.0000
9	0.00199	0.23692	7.1560	0.00246	0.46962	3.1018	184644333.	9.	0.0000
10	0.00202	0.23009	7.3924	0.00246	0.46342	3.1179	190988160.	6.	0.0000
11	0.00206	0.21851	7.5431	0.00246	0.45341	3.1451	199816233.	14.	0.0000
12	0.00211	0.20662	7.5298	0.00246	0.44391	3.1717	209209558.	[illegible]	0.0000
13	0.00212	0.20378	7.6044	0.00246	0.44308	3.1895	208660183.	12.	0.0000
14	0.00211	0.20922	7.9510	0.00246	0.44277	3.1953	197064712.	21.	0.0000
15	0.00211	0.21169	8.1737	0.00246	0.44321	3.2064	188813532.	21.	0.0000
16	0.00212	0.21136	8.4183	0.00246	0.44019	3.2206	189383619.	9.	0.0000
17	0.00212	0.21098	8.6039	0.00246	0.43912	3.2366	182894359.	9.	0.0000
18	0.00212	0.21264	8.9089	0.00246	0.43964	3.2487	174523228.	15.	0.0000
19	0.00212	0.21650	9.1800	0.00246	0.44219	3.2537	164795571.	18.	0.0000
20	0.00212	0.21588	9.5025	0.00246	0.43811	3.2706	164950415.	28.	0.0000
21	0.00220	0.20489	9.5839	0.00246	0.42954	3.3304	178873118.	516.	0.0000
22	0.00242	0.13531	5.4101	0.00246	0.31282	4.0435	147569083.	5.	0.0000
23	0.00245	0.11463	3.8892	0.00246	0.12352	17.3170	44069213.	4.	0.0000
24	0.00246	0.10314	3.0789	0.00246	0.10911	7.4116	28604151.	3.	0.0000
25	0.00246	0.10241	3.0415	0.00246	0.10751	7.0626	28593566.	1.	0.0000

MK48-,
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 8
TEST DATE 6-16-82

PROCESSING DATE 6-22-82
TEST DURATION, SEC 201.00

H Y B R I D B E A R I N G D A T A
TURBINE END (PAGE 1)

TIME SLICE NO	TURB BRG SUPPLY U/S PRESS (PSIA)	TURB BRG SUPPLY U/S TEMP (DEG R)	TURB BRG SUPPLY D/S ORIF PRESS (PSIA)	TURB BRG SUPPLY ORIF DP (PSID)	TURB BRG SUPPLY MANIF PRESS (PSIA)	TURB BRG DISCH PRESS (PSIA)	TURB BRG SUMP PRESS (PSIA)	-- TURBINE BRG -- DISCHARGE LINE PRESS (PSIA)	-- TURBINE BRG -- DISCHARGE LINE TEMP (DEG R)
1	2834.9	79.9	2786.6	153.8	2407.4	1119.0	1091.1	308.4	69.5
2	2629.2	78.3	2509.7	147.4	2305.1	1039.0	1011.8	286.4	67.2
3	2452.1	77.0	2343.2	132.2	2156.9	1020.6	991.8	277.1	66.0
4	2294.5	75.8	2196.8	119.4	2026.8	1007.7	979.8	276.0	65.5
5	2194.6	74.9	2066.5	108.6	1914.2	1014.5	992.2	293.2	64.1
6	2026.1	73.8	1943.7	98.8	1802.8	985.7	958.4	267.8	64.5
7	1911.8	72.9	1837.8	89.4	1709.4	978.5	950.4	264.2	64.1
8	1862.2	72.4	1789.6	89.4	1661.4	937.3	911.1	249.3	63.2
9	1810.3	72.3	1730.0	88.1	1609.4	878.3	857.4	205.4	60.3
10	1759.4	71.8	1686.4	87.6	1558.5	817.0	795.0	214.4	60.8
11	1709.8	71.6	1637.6	87.0	1507.2	752.6	731.4	188.4	59.2
12	1662.2	71.4	1589.2	86.2	1458.2	689.3	668.0	169.5	57.9
13	1622.3	71.1	1548.9	86.3	1420.1	661.8	640.8	164.8	57.5
14	1588.0	70.7	1518.2	88.4	1394.0	674.5	653.2	166.1	57.7
15	1553.3	70.4	1488.6	78.6	1366.2	677.8	656.0	162.2	57.3
16	1517.8	70.8	1450.2	77.6	1331.8	691.2	625.8	185.1	59.0
17	1485.0	69.9	1421.0	74.8	1306.2	649.2	626.6	176.9	58.5
18	1454.8	69.6	1392.6	72.4	1283.2	656.8	634.1	162.4	57.3
19	1627.0	69.3	1360.3	69.6	1262.0	666.7	645.3	163.2	57.5
20	1395.5	69.1	1337.0	67.2	1233.3	645.4	621.5	181.8	58.7
21	1355.3	68.7	1295.4	69.6	1187.5	562.5	543.2	157.1	57.0
22	771.6	65.2	731.2	41.6	662.3	142.6	126.5	90.7	45.5
23	212.1	59.4	205.4	0.3	199.3	105.5	89.0	40.6	43.7
24	144.8	56.8	141.0	0.0	137.5	61.8	48.6	28.5	41.0
25	141.9	56.5	137.0	0.0	133.7	52.8	42.3	26.9	40.5

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 8[illegible]
TEST DATE 6-16-82

PROCESSING DATE 6-22-82
TEST DURATION, SEC 201.00

H Y B R I D B E A R I N G D A T A
TURBINE END (PAGE 2)

TIME SLICE NO	SHAFT SPEED (RPM)	TURBINE CARTRIDGE SPEED (RPM)	TURBINE H/S BRG FLOW (LB/SEC)	LH2 DENSITY AT ORIF (PCF)	TURB BRG SUPPLY MANIF PRESS (PSIA)	TURB BRG DISCH PRESS (PSIA)	TURB BRG SUMP PRESS (PSIA)	HYDROSTATIC BEARING DELTA PRESS (PSID)
1	64581.	9.	0.4109	4.376	2487.4	1119.0	1091.1	1396.33
2	62757.	11.	0.4004	4.335	2306.1	1039.8	1011.8	1294.32
3	62312.	7.	0.3776	4.297	2156.9	1020.6	991.8	1165.00
4	62324.	4.	0.3575	4.264	2026.8	1007.7	979.8	1047.03
5	62274.	9.	0.3396	4.229	1914.2	1014.5	992.2	922.03
6	62020.	7.	0.3228	4.202	1802.8	985.7	958.4	844.34
7	61975.	2.	0.3059	4.172	1709.4	978.5	950.4	758.94
8	60437.	27.	0.3056	4.162	1661.4	937.3	911.1	750.96
9	57664.	9.	0.3026	4.140	1609.4	878.3	857.4	751.97
10	55641.	6.	0.3013	4.128	1558.5	817.0	795.0	763.55
11	52596.	14.	0.2996	4.109	1507.2	752.6	731.4	775.73
12	49554.	9.	0.2976	4.091	1458.2	689.3	668.0	790.16
13	48455.	12.	0.2973	4.078	1420.1	661.8	640.8	779.28
14	48987.	21.	0.2885	4.072	1394.0	674.5	653.2	740.86
15	49068.	21.	0.2831	4.062	1366.2	677.8	656.0	710.24
16	48620.	9.	0.2818	4.054	1331.8	649.0	625.8	705.96
17	48400.	9.	0.2754	4.040	1306.2	649.2	626.6	679.57
18	48449.	15.	0.2706	4.029	1283.2	656.8	634.1	649.08
19	48961.	18.	0.2652	4.024	1262.0	666.7	645.3	616.64
20	48687.	28.	0.2603	4.013	1233.3	645.4	621.5	611.82
21	42804.	521.	0.2643	4.001	1187.5	562.5	543.2	644.29
22	4307.	7.	0.1958	3.672	662.3	147.6	126.5	535.85
23	1872.	9.	0.0141	2.080	199.3	105.5	89.0	110.26
24	1358.	9.	0.0	0.836	137.5	61.8	48.6	88.95
25	1812.	3.	0.0	0.816	133.7	52.8	42.3	91.45

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 10A
TEST DATE 6-23-82

RERUN
7/7/82

PROCESSING DATE 6-30-82
TEST DURATION, SEC 203.00

COMMENTS . . .

TEST 10A
SLICES 2 THRU 11
PID711GH2 U/S VENT PI BAD. USED PID621GH2 SUPPLY PI FOR TURB FLOW.

AMBIENT PRESSURE		13.8303
LO2 VENTURI (GG)		
P/N V160268-SG3	UPSTREAM DIAMETER	0.0
S/N 8871	THROAT DIAMETER	0.0
	THROAT CD	0.0
GH2 VENTURI (TURB)		
P/N VP031223-SGP	UPSTREAM DIAMETER	2.3303
S/N 9731	THROAT DIAMETER	1.3385
	THROAT CD	0.9873
LH2 VENTURI (GG)		
P/N V329471-SGP	UPSTREAM DIAMETER	0.0
S/N 8873	THROAT DIAMETER	0.0
	THROAT CD	0.0
LH2 VENTURI (PUMP DISCH)		
P/N V320702-SGP	UPSTREAM DIAMETER	1.6833
S/N 8874	THROAT DIAMETER	0.7793
	THROAT CD	0.9760
	TURBINE SYSTEM EFF. AREA	0.70473
	TURBINE EXHAUST ORIFICE 4 EACH	0.31230
	5 EACH	0.32539
	1 EACH	0.33830

HYDROSTATIC BEARING SUPPLY SYSTEM
TURBINE INLET DUCT DIA 0.334 ORIFICE DIA 0.194
PUMP INLET DUCT DIA 0.402 ORIFICE DIA 0.175

MK48-1
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 10A
TEST DATE 6-23-82

PROCESSING DATE 8-30-82
TEST DURATION, SEC 203.00

G A S E O U S   H Y D R O G E N   T U R B I N E   D R I V E   P A R A M E T E R S

TIME SLICE NO	BEGIN TIME (SEC)	END TIME (SEC)	REG U/S PR (PSIA)	VENTURI U/S PR (PSIA)	VENTURI U/S TEMP (DEG R)	VENTURI DELTA PR (PSID)	SPIN VALVE POSN	SPIN VALVE U/S PR (PSIA)	FAC DUCT PR (PSIA)	TURB GH2 FLOW (LB/SEC)	SPEED (RPM)
1	95.975	96.120	4739.8	4739.8	525.55	0.38	1.03	4722.2	13.85	0.3156	8900.
2	96.965	97.110	4735.2	4735.2	526.01	1.26	2.30	4717.2	13.77	0.5588	25352.
3	97.996	98.099	4727.5	4727.5	528.41	0.63	3.06	4708.7	13.86	0.8371	30813.
4	98.98	99.131	4716.8	4716.9	521.80	0.87	5.20	4690.0	13.84	1.0620	34668.
5	99.976	100.121	4707.2	4707.2	520.37	1.10	6.35	4686.5	13.77	1.2432	37685.
6	100.966	101.110	4694.3	4694.3	520.95	1.20	6.64	4674.7	13.80	1.2934	38926.
7	101.997	102.130	4682.7	4682.7	530.23	1.37	6.67	4662.6	13.79	1.3077	38779.
8	104.967	105.152	4642.3	4642.3	531.79	1.59	7.44	4620.8	13.81	1.4302	40390.
9	109.998	110.143	4576.8	4576.0	523.15	1.61	7.49	4554.8	13.93	1.4336	41544.
10	114.989	115.133	4533.8	4533.8	533.57	1.61	7.63	4484.3	13.97	1.4272	41351.

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RUN NUMBER 10A
TEST DATE 5-23-82

PROCESSING DATE 6-30-82
TEST DURATION, SEC 203.00

H Y B R I D   B E A R I N G   D A T A
PUMP - END (PAGE 1)

TIME SLICE NO	PUMP BRG SUPPLY U/S PRESS (PSIA)	PUMP BRG SUPPLY TMP (DEG R)	PUMP BRG SUPPLY D/S ORIF PRESS (PSIA)	PUMP BRG SUPPLY ORIF DP (PSID)	PUMP BRG SUPPLY MANIF PRESS (PSIA)	--- PUMP BRG PAD PRESSURES --- 3.00 OCLOCK (PSIA)	9.00 OCLOCK (PSIA)	6.30 OCLOCK (PSIA)
1	386.6	76.0	367.6	22.8	377.8	144.0	151.9	13.8
2	454.2	77.8	428.4	28.4	439.2	155.4	152.5	13.9
3	502.6	78.3	472.9	31.9	483.5	186.2	194.9	13.9
4	546.2	78.7	514.6	32.6	525.4	219.5	211.1	13.4
5	559.1	78.5	533.7	36.3	544.5	217.8	224.1	13.9
6	589.5	78.6	553.5	39.9	563.7	232.6	218.2	13.6
7	595.0	78.5	558.4	40.0	567.8	242.2	249.7	13.7
8	614.4	78.4	575.6	42.4	584.3	251.8	259.0	13.8
9	632.4	76.8	591.1	44.4	603.4	259.5	256.0	13.9
10	660.7	75.8	615.2	47.5	628.2	265.3	275.4	13.7

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MK48
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

PAGE NO. 7

RUN NUMBER 10A
TEST DATE 6-23-82

PROCESSING DATE 6-30-82
TEST DURATION, SEC 299.99

H Y B R I D   B E A R I N G   D A T A
PUMP - END (PAGE 3)

TIME SLICE NO	PUMP BRG SUMP PRESSURE (PSIA)	PUMP BRG SUMP OUT PRESSURE (PSIA)	PUMP BRG SUMP OUT TEMP (DEG R)	SHAFT SPEED (RPM)	CARTRIDGE SPEED (RPM)	PUMP BRG FLOW (LB/SEC)	LH2 DENSITY AT ORIF (PCF)	AVERAGE PAD PRESSURE (PSIA)	PUMP BRG PRESSURE RATIO
1	97.7	49.9	44.9	8333.	1676.	0.0675	1.7759	162.9	0.1395
2	108.3	53.5	45.1	25357.	8101.	0.0812	1.9308	159.5	0.1660
3	108.1	51.9	45.3	33813.	15798.	0.0898	2.0367	115.6	0.2963
4	107.5	52.4	45.5	34648.	18330.	0.0954	2.1978	213.4	0.2462
5	18.1	54.1	45.9	37685.	24634.	0.1031	2.3048	221.9	0.2575
6	108.3	54.1	45.8	38526.	31918.	0.1064	2.3936	215.4	0.2775
7	108.7	54.3	45.7	38770.	33823.	0.1116	2.4978	246.0	0.2901
8	106.6	56.2	45.9	40393.	40318.	0.1155	2.5829	254.3	0.3097
9	108.3	55.2	46.3	41566.	41517.	0.1225	2.6637	252.5	0.3135
10	99.0	55.9	46.1	41351.	41262.	0.1304	2.8106	273.4	0.3126

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RUN NUMBER 10 A
TEST DATE 6-23-82

PROCESSING DATE 6-30-82
TEST DURATION, SEC 203.00

H Y B R I D B E A R I N G D A T A
PUMP - END (PAGE 1)

TIME SLICE NO	BRG DELTA P ORIFIC PSID	BRG DELTA P FILM PSID	BRG DELTA P TOTAL PSID	ORIFICE RESISTANCE SEC**2/ IN-IN**2	FLUID FILM RESISTANCE SEC**2/ IN-IN**2	POISEUILLE REYNOLDS NO	COUETTE REYNOLDS NO	LAMBDA BRG NO	TORQUE FLUID FILM (TEMP) IN-LBS
1	234.8	35.2	270.1	51542.2	7772.5	63763534.	576.	0.00312	-659.1087
2	275.7	55.2	330.9	41902.2	8357.1	77482024.	2235.	0.00353	-154.7215
3	297.9	77.4	375.3	36166.5	9637.4	81933197.	5661.	0.01094	-88.5068
4	315.0	102.9	417.9	34579.4	11295.9	94118454.	7237.	0.00136	-74.6648
5	322.5	111.9	434.4	30367.6	10526.1	96412049.	9975.	0.00164	-58.0173
6	328.3	126.1	454.4	27959.4	10697.9	85408437.	12971.	0.00171	-46.3440
7	321.9	137.3	459.2	26323.1	11211.2	80216448.	15716.	0.00249	-38.5164
8	330.4	148.2	478.7	24752.8	11104.4	91329347.	16425.	0.00257	-37.9476
9	337.8	154.3	492.1	22511.2	10292.4	96837338.	17811.	0.00253	-35.8599
10	354.8	161.4	516.2	20861.6	9419.6	104818514.	19475.	0.00254	-35.9120

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MK49-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

PAGE NO. 9

RUN NUMBER 16A
TEST DATE 6-23-82

PROCESSING DATE 6-30-82
TEST DURATION, SEC 209.90

H Y B R I D   B E A R I N G   D A T A
PUMP AND TURBINE END (PAGE 4)

	PUMP			TURBINE					
TIME SLICE NO	HS BRG CLEARANCE RADIAL IN	VISCOSITY PUMP BRG LB-HR/FT**2 * FT)	CSUBP PUMP BRG BTU/ LB-R	HS BRG CLEARANCE RADIAL IN	VISCOSITY TURB BRG LB-HR/FT**2 * FT)	CSUBP TURB BRG BTU/ LB-R	POISEUILLE REYNOLDS NI	COUETTE REYNOLDS NO	LAMBDA TURB NO
1	0.00245	0.13612	3.1733	0.00246	0.14380	4.3300	45602843.	5.	0.0377
2	0.00244	0.14077	3.3544	0.00246	0.17174	5.3127	77486953.	198.	0.0077
3	0.00241	0.14424	3.3847	0.00246	0.19883	5.5075	1543918[illegible].	755.	0.0091
4	0.00240	0.14673	3.5737	0.00245	0.22616	5.1174	132060085.	1337.	0.0091
5	0.00236	0.14813	3.6016	0.00246	0.24053	4.7036	139372415.	389.	0.0390
6	0.00230	0.14993	3.8170	0.00244	0.26174	4.5685	155350755.	14.	0.0030
7	0.00 23	0.15167	3.9312	0.00246	0.25781	4.4403	168411466.	15.	0.0370
8	0.00222	0.15336	4.0360	0.00246	0.29536	4.1600	194386763.	10.	0.0003
9	0.00223	0.15457	4.3453	0.01246	0.31763	3.8133	166428567.	6.	0.0000
10	0.00221	0.15625	4.6324	0.00245	0.35640	3.5000	234226071.	12.	0.0000

RUN NUMBER 10A
TEST DATE 6-23-82

PROCESSING DATE 6-30-82
TEST DURATION, SEC 203.99

H Y B R I D   B E A R I N G   D A T A
TURBINE END (PAGE 1)

TIME SLICE NO	TURB BRG SUPPLY U/S PRESS (PSIA)	TURB BRG SUPPLY U/S TEMP (DEG R)	TURB BRG SUPPLY D/S ORIF PRESS (PSIA)	TURB BRG SUPPLY ORIF DP (PSID)	TURB BRG SUPPLY MANIF PRESS (PSIA)	TURB BRG DISCH PRESS (PSIA)	TURB BRG SUMP PRESS (PSIA)	-- TURBINE BRG -- DISCHARGE LINE PRESS (PSIA)	TEMP (DEG R)
1	391.4	78.1	293.3	13.6	276.9	127.3	190.7	62.0	69.2
2	484.3	82.5	469.3	23.0	441.1	253.9	232.7	71.0	48.5
3	662.9	84.1	640.7	29.4	601.1	322.0	330.9	89.8	50.7
4	816.4	94.2	773.3	34.8	779.6	375.8	353.9	103.5	52.2
5	97 .1	84.0	890.3	45.3	827.4	430.2	407.3	116.2	53.6
6	1004.1	83.5	963.4	51.7	891.6	448.7	435.9	112.5	53.2
7	1052.7	83.3	1039.7	55.2	971.0	452.8	427.8	118.8	53.7
8	117 .8	82.8	1121.4	63.9	1039.8	475.1	448.9	133.5	55.0
9	1240.2	79.4	1188.7	65.2	1201.0	511.8	455.7	164.3	56.0
10	1422.7	77.1	1358.5	70.2	1241.4	529.4	493.3	146.7	56.2

ORIGINAL PAGE IS
OF POOR QUALITY

MK48-
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 10A
TEST DATE 6-23-82

PROCESSING DATE 6-30-82
TEST DURATION, SEC 203.00

HYBRID BEARING DATA
TURBINE END (PAGE 2)

TIME SLICE NO	SHAFT SPEED (RPM)	TURBINE CARTRIDGE SPEED (RPM)	TURBINE GAS BRG FLOW (LB/SEC)	LH2 DENSITY AT ORIF (PCF)	TURB BRG SUPPLY MANIF PRESS (PSIA)	TURB BRG DISCH PRESS (PSIA)	TURB BRG SUMP PRESS (PSIA)	HYDROSTATIC BEARING DELTA PRESS (PSID)
1	8300.	16.	0.0517	1.002	276.0	127.3	120.7	147.29
2	25352.	411.	0.0914	1.661	461.1	253.0	222.7	238.36
3	30813.	1300.	0.1267	2.249	631.1	372.0	300.0	331.09
4	34661.	2074.	0.1520	2.669	730.6	375.9	353.0	396.69
5	37685.	551.	0.1808	2.875	927.4	423.3	407.3	420.11
6	38526.	19.	0.1993	3.240	891.6	448.7	425.0	465.76
7	3877 .	21.	0.2076	3.110	931.0	452.8	437.8	534.11
8	40309.	13.	0.2205	3.293	1033.0	475.1	448.0	581.06
9	41564.	19.	0.2301	3.608	1061.0	511.8	485.7	626.20
10	41351.	13.	0.2228	3.766	1241.4	520.4	493.0	769.69

ORIGINAL PAGE IS
OF POOR QUALITY

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 10 Ø
TEST DATE 6-23-82

RERUN
7/8/82

PROCESSING DATE 6-30-82
TEST DURATION, SEC 203.00

COMMENTS . . .

TEST 108
SLICES 12 THRU 39
PID71(GH2 US VENT P) BAD. USED PID62(GH2 SUPPLY P) FOR TURB. FLOW.

AMBIENT PRESSURE 13.8000

LO2 VENTURI (GG)		
P/N V160248-SGR	UPSTREAM DIAMETER	0.0
S/N 8871	THROAT DIAMETER	0.0
	THROAT CD	0.0
GH2 VENTURI (TURB)		
P/N VP031200-SGR	UPSTREAM DIAMETER	2.3000
S/N 9731	THROAT DIAMETER	1.3085
	THROAT CD	0.9873
LH2 VENTURI (GG)		
P/N V320471-SGR	UPSTREAM DIAMETER	0.0
S/N 8873	THROAT DIAMETER	0.0
	THROAT CD	0.0
LH2 VENTURI (PUMP DISCH)		
P/N V320709-SGR	UPSTREAM DIAMETER	1.6890
S/N 8874	THROAT DIAMETER	0.7090
	THROAT CD	0.9760

TURBINE SYSTEM EFF. AREA 0.70470
TURBINE EXHAUST ORIFICE 4 EACH 0.31200
4 EACH 0.32500
1 EACH 0.30800

HYDROSTATIC BEARING SUPPLY SYSTEM
TURBINE INLET DUCT DIA 0.334 ORIFICE DIA 0.194
PUMP INLET DUCT DIA 0.402 ORIFICE DIA 0.175

ORIGINAL PAGE IS
OF POOR QUALITY

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 108
TEST DATE 6-23-82

PROCESSING DATE 6-30-82
TEST DURATION, SEC 203.00

G A S E O U S   H Y D R O G E N   T U R B I N E   D R I V E   P A R A M E T E R S

TIME SLICE NO	BEGIN TIME (SEC)	END TIME (SEC)	REG U/S PR (PSIA)	VENTURI U/S PR (PSIA)	VENTURI U/S TEMP (DEG R)	VENTURI DELTA PR (PSID)	SPIN VALVE POSN	SPIN VALVE U/S PR (PSIA)	FAC DUCT PR (PSIA)	TURB GH2 FLOW (LB/SEC)	SPEED (RPM)
1	119.980	120.124	4421.3	4421.3	534.09	1.72	7.82	4401.4	13.85	1.4653	41514.
2	124.970	125.156	4353.8	4353.8	534.26	1.69	7.96	4332.9	13.89	1.4431	41419.
3	129.961	130.146	4290.0	4290.0	534.56	1.66	7.95	4267.7	13.94	1.4238	41544.
4	134.993	135.137	4223.4	4223.4	534.58	1.75	8.21	4201.9	13.90	1.4515	42211.
5	139.983	140.128	4152.8	4152.8	534.68	1.65	8.22	4133.6	13.97	1.3994	41676.
6	144.974	145.159	4062.8	4062.8	534.90	1.71	8.33	4042.3	13.94	1.4109	42366.
7	149.964	150.150	3989.7	3989.7	534.72	1.82	8.71	3968.4	13.97	1.4445	42669.
8	154.996	155.141	3925.9	3925.9	534.61	1.88	9.03	3905.7	13.94	1.4587	42794.
9	159.987	160.131	3863.3	3863.3	534.56	2.99	11.63	3837.1	14.40	1.8282	45679.
10	160.977	161.121	3842.8	3842.8	534.54	6.65	17.73	3806.4	21.31	2.7167	54099.
11	161.966	162.111	3814.9	3814.9	534.56	12.74	24.95	3758.8	31.97	3.7459	62243.
12	162.998	163.101	3778.0	3778.0	534.37	21.43	32.94	3695.5	43.25	4.8299	69163.
13	163.987	164.132	3730.9	3730.9	534.06	32.71	41.92	3613.2	54.59	5.9700	75033.
14	164.977	165.122	3678.9	3678.9	533.20	41.74	48.98	3536.4	62.01	6.6278	78784.
15	165.967	166.112	3625.4	3625.4	532.23	45.25	52.46	3471.2	64.48	6.8444	79884.
16	166.998	167.101	3602.7	3602.7	532.00	0.07	-0.91	3583.3	13.97	0.2612	54029.
17	167.988	168.133	3604.1	3604.1	532.12	0.0	-0.81	971.9	13.97	0.0013	35708.
18	168.978	169.122	3600.1	3600.1	532.36	0.0	-0.75	352.8	13.97	0.0013	25778.
19	169.968	170.112	3604.4	3604.4	532.50	0.0	-0.74	154.5	13.97	0.0013	17953.
20	170.999	171.102	3603.9	3603.9	532.73	0.0	-0.70	70.6	13.97	0.0013	13327.
21	171.989	172.133	3604.9	3604.9	532.82	0.0	-0.67	33.7	13.97	0.0013	10891.
22	172.979	173.123	3607.0	3607.0	532.85	0.0	-0.65	15.3	13.97	0.0014	8998.
23	175.000	175.144	3608.9	3608.9	533.11	0.0	-0.64	13.6	13.97	0.0014	6653.
24	179.990	180.135	3614.0	3614.0	533.46	0.0	-0.64	13.6	13.97	0.0014	4213.
25	184.981	185.125	3619.0	3619.0	533.70	0.0	-0.64	14.0	13.97	0.0014	3083.
26	189.971	190.157	3623.9	3623.9	533.83	0.0	-0.63	13.6	13.97	0.0014	2212.
27	194.962	195.148	3630.3	3630.3	533.94	0.0	-0.64	13.6	13.97	0.0015	1293.
28	199.994	200.138	3634.1	3634.1	534.04	0.0	-0.61	13.6	13.97	0.0015	0.

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 108
TEST DATE 6-23-82

PROCESSING DATE 6-30-82
TEST DURATION, SEC 203.00

H Y B R I D B E A R I N G D A T A
PUMP - END (PAGE 1)

TIME SLICE NO	PUMP BRG SUPPLY U/S PRESS (PSIA)	PUMP BRG SUPPLY TEMP (DEG R)	PUMP BR. SUPPLY D/S ORIF PRESS (PSIA)	PUMP BRG SUPPLY ORIF DP (PSID)	PUMP BRG SUPPLY MANIF PRESS (PSIA)	--- PUMP BRG PAD PRESSURES --- 3.00 OCLOCK (PSIA)	9.00 OCLOCK (PSIA)	6.30 OCLOCK (PSIA) ---
1	646.7	79.4	604.4	43.9	615.1	262.4	272.0	13.6
2	637.5	79.1	596.3	42.5	606.4	260.2	269.1	13.8
3	954.9	81.0	879.8	71.1	890.6	340.7	357.4	13.5
4	1193.7	81.5	1094.9	94.2	1104.3	396.6	421.6	13.9
5	1200.3	80.7	1098.4	97.2	1109.2	393.6	416.3	14.3
6	1195.9	90.0	1104.5	88.3	1114.8	423.8	444.7	13.9
7	1185.6	92.7	1097.4	84.2	1108.6	431.6	450.9	13.9
8	1183.1	93.2	1095.9	82.9	1106.8	432.6	450.8	13.9
9	1185.8	93.3	1098.0	82.4	1109.0	446.0	465.3	13.9
10	1190.0	93.3	1105.7	78.7	1117.3	490.1	513.9	13.9
11	1187.8	93.0	1109.9	72.5	1121.5	540.8	570.5	13.9
12	1182.5	92.7	1114.8	63.1	1127.6	601.2	638.3	13.1
13	1169.6	92.6	1111.3	53.8	1123.0	677.6	698.3	13.6
14	1166.1	92.1	1102.6	58.1	1115.0	581.4	600.6	14.0
15	1167.7	91.7	1105.6	57.1	1118.3	549.7	588.8	13.9
16	985.0	90.2	921.0	59.8	933.5	465.0	491.2	13.9
17	959.3	90.1	892.3	63.5	903.0	391.2	409.5	16.2
18	900.6	82.6	833.1	64.8	843.6	304.3	311.0	15.9
19	762.9	70.3	701.1	59.9	710.8	246.2	251.6	15.6
20	517.0	64.6	480.6	36.4	489.5	180.7	184.4	15.5
21	317.4	62.1	306.3	11.8	316.0	141.1	142.6	15.2
22	235.6	61.1	233.0	1.4	243.2	109.7	110.7	14.7
23	174.2	58.8	174.6	0.3	184.5	65.8	64.3	14.4
24	171.9	54.7	124.6	0.0	135.1	46.1	45.8	13.9
25	99.8	52.5	102.9	0.0	110.4	40.5	41.5	13.9
26	63.7	69.3	68.3	-4.0	74.9	30.8	30.8	15.4
27	34.2	91.7	39.7	-5.7	43.9	23.2	23.1	15.2
28	18.9	106.8	23.2	-7.2	25.6	19.0	20.0	14.4

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 10
TEST DATE 6-23-82

PROCESSING DATE 6-30-82
TEST DURATION, SEC 203.00

H Y B R I D B E A R I N G D A T A
PUMP - END (PAGE 2)

TIME SLICE NO	PUMP BRG SUMP PRESSURE (PSIA)	PUMP BRG SUMP OUT PRESSURE (PSIA)	PUMP BRG SUMP OUT TEMP (DEG R)	SHAFT SPEED (RPM)	CARTRIDGE SPEED (RPM)	PUMP BRG FLOW (LB/SEC)	LH2 DENSITY AT ORIF (PCF)	AVERAGE PAD PRESSURE (PSIA)	PUMP BRG PRESSURE RATIO
1	108.5	55.0	46.0	41514.	41460.	0.1184	2.5156	267.2	0.3134
2	107.8	54.8	45.9	41419.	41428.	0.1163	2.5099	264.6	0.3145
3	111.5	55.4	46.0	41544.	41567.	0.1668	3.0804	349.1	0.3050
4	112.4	54.9	45.9	42211.	42215.	0.2006	3.3631	409.1	0.2991
5	111.6	54.3	45.8	41676.	41652.	0.2051	3.4060	405.0	0.2941
6	113.7	55.1	46.0	42766.	42437.	0.1836	3.0056	434.2	0.3202
7	11 9	54.6	45.9	42659.	42663.	0.1755	2.8822	441.3	0.3298
8	112.6	54.5	45.8	42794.	42745.	0.1735	2.8582	441.7	0.3310
9	112.1	54.5	45.8	45679.	45879.	0.1729	2.8574	455.7	0.3447
10	110.3	57.4	46.2	54039.	54313.	0.1691	2.8632	502.0	0.3890
11	108.5	61.1	46.9	62743.	62405.	0.1626	2.8700	555.7	0.4414
12	106.5	63.2	47.1	69143.	69323.	0.1517	2.8747	619.8	0.5026
13	106.1	71.4	54.9	75033.	56459.	0.1399	2.8647	687.9	0.5722
14	104.9	75.7	48.9	78784.	55677.	0.1457	2.8791	591.0	0.4812
15	107.1	75.0	48.8	79884.	52727.	0.1450	2.8990	569.3	0.4570
16	106.3	106.4	52.8	54029.	53481.	0.1427	2.6789	478.1	0.4495
17	110.9	69.6	56.1	35708.	35427.	0.1458	2.6364	400.4	0.3654
18	112.6	54.9	46.0	25778.	25614.	0.1547	2.9099	307.6	0.2669
19	110.8	50.8	45.2	17953.	17851.	0.1604	3.3810	248.9	0.2302
20	101.4	48.1	44.8	13327.	13301.	0.1245	3.3497	182.6	0.2091
21	79.1	40.3	43.3	10891.	10921.	0.0675	3.0402	141.9	0.2647
22	63.8	35.2	42.2	8998.	6625.	0.0338	2.6302	110.2	0.2585
23	50.5	32.0	41.5	6653.	6505.	0.0063	1.1725	65.1	0.1090
24	33.1	26.5	41.5	4213.	4278.	0.0	0.6746	45.9	0.1283
25	27.8	25.1	52.8	3083.	3025.	0.0	0.5294	41.0	0.1593
26	24.0	23.2	77.0	2212.	2155.	0.0	0.1872	30.8	0.1339
27	21.0	20.9	86.6	1293.	1231.	0.0	0.0713	23.2	0.0932
28	18.5	18.5	92.1	0.	3.	0.0	0.0334	19.5	0.1334

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 10█
TEST DATE 6-23-82

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TEST DURATION, SEC 203.00

H Y B R I D B E A R I N G D A T A
PUMP - END (PAGE 3)

TIME SLICE NO	BRG DELTA P ORIFICE PSID	BRG DELTA P FILM PSID	BRG DELTA P TOTAL PSID	ORIFICE RESISTANCE SEC**2/ LB-IN**2	FLUID FILM RESISTANCE SEC**2/ LB-IN**2	POISEUILLE RENOLDS NO	COUETTE RENOLDS NO	LAMBDA BRG NO	TORQUE FLUID FILM (TEMP) IN-LBS
1	347.8	158.8	506.6	24803.4	11319.9	94241584.	16959.	0.00259	-39.1345
2	341.8	156.8	498.6	25249.2	11585.6	93134501.	16946.	0.00261	-[illegible].3084
3	541.5	237.6	779.2	19459.2	8537.9	142834352.	18775.	0.00201	-50.0235
4	695.2	296.7	991.9	17278.2	7374.3	172606975.	20001.	0.00182	-58.4216
5	704.2	293.4	997.6	16746.0	6977.4	175866050.	19911.	0.00178	-59.2590
6	680.5	320.5	1001.0	20194.6	9511.0	158873541.	18194.	0.00179	-66.5490
7	667.3	328.4	995.7	21654.0	10655.8	15.751231.	17601.	0.00182	-67.5945
8	665.2	329.1	994.2	22102.9	10935.1	150075025.	17482.	0.00183	-67.5316
9	653.3	343.6	996.9	21853.3	11493.5	142481737.	18460.	0.00205	-62.8470
10	615.3	391.8	1007.0	21510.9	13696.7	122196911.	21837.	0.00281	-51.4366
11	565.8	447.1	1013.0	21409.5	16919.2	100859746.	24652.	0.00385	-42.2504
12	507.9	513.2	1021.1	22063.1	22296.2	81822182.	26822.	0.00518	-35.0612
13	435.1	581.9	1016.9	22237.6	29739.0	113107314.	25702.	0.00159	2.3513
14	524.0	486.1	1010.1	24676.4	22890.1	116244614.	23873.	0.00325	-39.8036
15	549.0	462.1	1011.1	26098.2	21968.6	126642492.	23042.	0.00287	-41.4307
16	455	371.8	827.1	22371.2	18266.2	104977474.	21944.	0.00323	-3.7576
[illegible]	502.	289.4	792.1	23660.8	13624.6	136907395.	14931.	0.00167	6.6213
[illegible]	536.0	195.1	731.1	22387.2	8149.0	158539765.	11342.	0.00108	-79.9604
[illegible]	461.9	138.1	600.1	17957.0	5370.3	178560387.	9607.	0.00079	-79.2795
	307.0	81.1	388.1	19816.0	5237.6	95880976.	6043.	0.00087	-66.1249
	174.2	62.7	236.9	38266.7	13777.0	72821601.	4860.	0.00087	-44.6245
	133.0	46.4	179.4	116768.3	40702.5	48086445.	2394.	0.00064	-42.4660
	119.4	14.6	134.0	2990269.2	365916.3	28908268.	1707.	0.00075	-13.2975
	87.2	12.8	100.1	************	************	18086628.	870.	0.00063	0.0
	19.5	13.2	82.6	************	************	14585170.	577.	0.00052	0.0
[illegible]	44.1	6.8	51.0	************	************	3309055.	188.	0.00067	0.0
[illegible]	20.8	2.1	22.9	************	************	569204.	51.	0.00082	0.0
28	6.1	0.9	7.1	************	************	102317.	0.	0.00000	0.0

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 108
TEST DATE 4-23-82

PROCESSING DATE 6-30-82
TEST DURATION, SEC 203.00

H Y B R I D   B E A R I N G   D A T A
PUMP AND TURBINE END (BAGE 4)

TIME SLICE NO	PUMP: HS BRG CLEARANCE RADIAL IN	PUMP: VISCOSITY PUMP BRG LB-HR/FT**2 * E10	PUMP: CSUMP PUMP BRG BTU/ LB-R	TURBINE: HS BRG CLEARANCE RADIAL IN	TURBINE: VISCOSITY TURB BRG LB-HR/FT**2 * E10	TURBINE: CSUMP TURB BRG BTU/ LB-R	TURBINE: POISEUILLE RENOLDS ND	TURBINE: COUETTE RENOLDS ND	TURBINE: LAMBDA TURB ND
1	0.00220	0.15594	4.0653	0.00246	0.33661	3.6140	273551567.	49.	0.0000
2	0.00220	0.15536	4.0729	0.00246	0.31886	3.8015	235640066.	13.	0.0000
3	0.00220	0.17454	4.7370	0.00246	0.38062	3.3139	326299454.	10.	0.0000
4	0.00220	0.19159	5.2653	0.00246	0.41588	3.1426	351463498.	15.	0.0000
5	0.00220	0.19193	5.4148	0.00246	0.42368	3.1122	349268647.	7.	0.0000
6	0.00219	0.18923	4.2352	0.00246	0.44110	2.9671	491111609.	12.	0.0000
7	0.00219	0.18958	4.0486	0.00246	0.39650	3.1347	485339730.	5.	0.0000
8	0.00219	0.18960	4.0149	0.00246	0.38809	3.1649	484854644.	17.	0.0000
9	0.00215	0.19224	4.0644	0.00246	0.40752	3.1020	481515311.	12.	0.0000
10	0.00204	0.20103	4.2470	0.00246	0.44923	2.9912	449368464.	12.	0.0000
11	0.00191	0.21203	4.4481	0.00246	0.49569	2.8919	397184151.	12.	0.0000
12	0.00179	0.27667	4.5246	0.00246	0.51647	2.8777	334365995.	19.	0.0000
13	0.00201	0.24065	4.7734	0.00246	0.52978	2.8722	292481988.	17.	0.0000
14	0.00202	0.22166	4.6292	0.00246	0.54256	2.8631	259037077.	14.	0.0000
15	0.00206	0.21643	4.6148	0.00246	0.54765	2.8675	239575237.	557.	0.0000
16	0.00205	0.19846	4.4347	0.00246	0.41960	2.9835	578407416.	8.	0.0000
17	0.00227	0.18303	4.0536	0.00246	0.34074	3.2911	529665175.	11.	0.0000
18	0.00235	0.16479	4.1131	0.00246	0.24631	3.6300	385198236.	8.	0.0000
19	0.00240	0.15213	5.7332	0.00246	0.30023	3.9512	207310674.	7.	0.0000
20	0.00242	0.15749	5.4525	0.00246	0.23181	5.3815	78299387.	4.	0.0000
21	0.00243	0.12479	4.4774	0.00246	0.16164	10.4977	55371826.	6.	0.0000
22	0.00245	0.11763	3.7011	0.00246	0.12381	42.2999	54979273.	262.	0.0001
23	0.00245	0.10614	3.0555	0.00246	0.11466	10.3679	37244154.	3.	0.0000
24	0.00245	0.09857	2.9323	0.00246	0.10137	5.6750	23866554.	2.	0.0000
25	0.00245	0.07488	2.9265	0.00246	0.09697	4.6858	17235847.	-1.	-0.0000
26	0.00245	0.11809	2.6046	0.00246	0.11879	2.7609	3079418.	1.	0.0000
27	0.00246	0.14755	2.5398	0.00246	0.14550	2.5610	328291.	0.	0.0000
28	0.00246	0.16620	2.5641	0.00246	0.16315	2.5550	12365.	0.	0.0000

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OF POOR QUALITY

RUN NUMBER 10
TEST DATE 6-23-82

PROCESSING DATE 6-30-82
TEST DURATION, SEC 203.00

H Y B R I D B E A R I N G D A T A
TURBINE END (PAGE 1)

TIME SLICE NO	TURB BRG SUPPLY U/S PRESS (PSIA)	TURB BRG SUPPLY U/S TEMP (DEG R)	TURB BRG SUPPLY D/S ORIF PRESS (PSIA)	TURB BRG SUPPLY ORIF DP (PSID)	TURB BRG SUPPLY MANIF PRESS (PSIA)	TURB BRG DISCH PRESS (PSIA)	TURB BRG SUMP PRESS (PSIA)	-- TURBINE BRG -- DISCHARGE PRESS (PSIA)	LINE TEMP (DEG R)
1	1558.9	81.8	1483.1	90.7	1354.8	530.5	502.2	146.4	56.1
2	1391.7	82.0	1327.8	79.9	1216.3	521.9	491.9	144.7	56.0
3	1860.3	79.3	1764.4	114.8	1602.6	545.2	514.5	148.7	56.3
4	2094.5	77.7	1989.3	124.9	1805.0	566.7	533.9	153.1	56.6
5	2108.9	76.6	1994.6	132.7	1807.4	556.8	524.2	151.4	56.5
6	2903.3	82.8	2764.2	170.4	2502.8	621.1	575.6	160.9	59.1
7	2673.0	88.1	2534.6	163.2	2304.2	613.1	571.2	160.0	60.4
8	2631.3	89.1	2498.1	157.8	2272.1	613.0	570.9	160.9	60.8
9	2768.2	88.1	2628.2	168.8	2389.6	670.8	627.8	174.5	61.8
10	3026.2	86.1	2885.2	170.3	2624.0	855.2	817.2	222.5	65.6
11	3255.9	83.6	3100.0	192.3	2827.5	1069.4	1037.5	269.5	69.1
12	3244.5	83.0	3102.2	179.8	2846.3	1280.6	1256.3	283.1	70.4
13	3223.7	82.8	3090.7	170.5	2852.0	1440.6	1411.9	355.9	75.3
14	3205.1	82.4	3083.6	159.9	2858.5	1565.8	1540.8	385.4	77.6
15	3166.5	82.0	3049.3	155.5	2835.3	1619.5	1600.6	364.0	77.1
16	2903.3	83.4	2750.5	186.2	2486.8	373.8	339.6	135.3	58.7
17	2273.0	86.1	2158.0	145.3	1959.8	294.5	263.9	83.7	52.2
18	1550.4	81.8	1478.5	90.4	1341.8	218.6	190.9	59.4	46.8
19	958.7	69.6	913.3	58.1	823.5	169.3	146.0	53.6	46.0
20	503.8	64.3	480.0	26.5	436.7	132.3	112.8	46.7	44.9
21	307.9	62.4	297.0	9.6	277.6	99.7	84.3	38.2	43.3
22	231.0	61.0	224.8	3.2	215.4	80.4	66.0	33.5	42.2
23	173.2	58.9	170.1	0.0	164.1	61.8	49.6	29.4	41.3
24	121.4	54.8	120.0	0.0	113.2	41.3	32.1	25.6	40.4
25	98.8	52.6	97.2	0.0	91.2	34.6	27.3	24.0	51.8
26	64.2	6 .2	63.1	0.0	58.7	28.3	25.1	21.9	77.5
27	35.0	89.9	35.4	0.0	32.0	22.9	20.3	20.1	104.7
28	19.9	104.3	21.9	0.0	19.0	19.4	18.1	17.9	103.6

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 10[illegible]
TEST DATE 6-23-82

PROCESSING DATE 6-30-82
TEST DURATION, SEC 203.00

HYBRID BEARING DATA
TURBINE END (PAGE 2)

TIME SLICE NO	SHAFT SPEED (RPM)	TURBINE CARTRIDGE SPEED (RPM)	TURBINE H/S BRG FLOW (LB/SEC)	LH2 DENSITY AT ORIF (PCF)	TURB BRG SUPPLY MANIF PRESS (PSIA)	TURB BRG DISCH PRESS (PSIA)	TURB BRG SUMP PRESS (PSIA)	HYDROSTATIC BEARING DELTA PRESS (PSID)
1	41514.	55.	0.2892	3.677	1354.8	530.5	502.2	852.59
2	41419.	15.	0.2662	3.535	1216.3	521.9	493.9	722.39
3	41544.	10.	0.3374	3.953	1602.6	545.2	514.5	1088.06
4	42211.	16.	0.3594	4.121	1805.0	566.7	533.9	1271.08
5	41676.	7.	0.3722	4.160	1807.4	556.8	524.2	1283.16
6	42366.	13.	0.4303	4.331	2502.8	621.1	575.6	1927.11
7	42669.	6.	0.4102	4.109	2304.2	613.1	571.2	1732.99
8	42794.	19.	0.4012	4.066	2272.1	613.0	570.9	1701.22
9	45679.	13.	0.4193	4.150	2389.6	670.8	627.8	1761.83
10	54099.	13.	0.4286	4.298	2624.0	855.2	817.2	1806.82
11	62243.	13.	0.4627	4.436	2827.5	1069.4	1037.5	1789.76
12	69143.	21.	0.4479	4.445	2846.3	1280.6	1256.3	1590.00
13	75033.	19.	0.4360	4.443	2852.0	1440.6	1411.9	1440.08
14	78784.	16.	0.4224	4.446	2858.5	1565.8	1540.8	1317.69
15	79984.	629.	0.4164	4.441	2835.3	1619.5	1600.6	1234.67
16	54029.	9.	0.4491	4.316	2486.8	373.8	339.6	2147.28
17	35708.	13.	0.3782	3.922	1959.8	294.5	263.9	1695.93
18	25778.	10.	0.2886	3.669	1341.8	218.6	190.9	1150.90
19	17953.	10.	0.2307	3.654	823.5	169.3	146.0	677.49
20	13327.	9.	0.1491	3.348	436.7	132.3	112.8	323.90
21	10891.	16.	0.0844	2.944	277.6	99.7	84.3	193.32
22	8998.	689.	0.0458	2.612	215.4	80.4	65.0	149.41
23	6653.	10.	0.0	1.123	164.1	61.8	49.5	114.48
24	4213.	10.	0.0	0.662	113.2	41.3	32.1	81.05
25	3083.	-5.	0.0	0.516	91.2	34.6	27.1	63.94
26	2212.	10.	0.0	0.189	58.7	28.3	25.1	33.66
27	1293.	3.	0.0	0.075	32.0	22.9	20.3	11.71
28	0.	10.	0.0	0.036	19.0	19.4	18.1	0.91

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

PAGE 11. 1

RUN NUMBER 11 A
TEST DATE 6-30-82

REDUN
7/7/82

PROCESSING DATE 7-01-82
TEST DURATION, SEC 370.00

COMMENTS . . .
PID109(LND INL PR) BAD. USED PID097.
TEST 11A

AMBIENT PRESSURE		13.8000
LO2 VENTURI (GG) P/N V160248-SGR S/N 8871	UPSTREAM DIAMETER	0.0
	THROAT DIAMETER	0.0
	THROAT CD	0.0
GH2 VENTURI (TURB) P/N VP031200-SGR S/N 9731	UPSTREAM DIAMETER	2.3000
	THROAT DIAMETER	1.3085
	THROAT CD	0.9873
LH2 VENTURI (GG) P/N V320471-SGR S/N 8873	UPSTREAM DIAMETER	0.0
	THROAT DIAMETER	0.0
	THROAT CD	0.0
LH2 VENTURI (PUMP DISCH) P/N V320709-SGR S/N 8874	UPSTREAM DIAMETER	1.6890
	THROAT DIAMETER	0.7090
	THROAT CD	0.9760
	TURBINE SYSTEM EFF. AREA	0.70470
	TURBINE EXHAUST ORIFICE 4 EACH	0.31200
	4 EACH	0.32500
	1 EACH	0.30800
	4 EACH	0.37500
	TURBINE EXHAUST EFF. AREA	1.03600

HYDROSTATIC BEARING SUPPLY SYSTEM
TURBINE INLET DUCT DIA 0.334 ORIFICE DIA 0.194
PUMP INLET DUCT DIA 0.402 ORIFICE DIA 0.175

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 11A
TEST DATE 6-30-82

PROCESSING DATE 7-01-82
TEST DURATION, SEC 370.00

G A S E O U S H Y D R O G E N T U R B I N E D R I V E P A R A M E T E R S

TIME SLICE NO	BEGIN TIME (SEC)	END TIME (SEC)	REG U/S PR (PSIA)	VENTURI U/S PR (PSIA)	VENTURI U/S TEMP (DEG R)	VENTURI DELTA PR (PSID)	SPIN VALVE POSN	SPIN VALVE U/S PR (PSIA)	FAC DUCT PR (PSIA)	TURB GH2 FLOW (LB/SEC)	SPEED (RPM)
1	259.964	260.233	4699.9	4688.4	522.74	0.64	4.89	4637.6	13.88	0.9042	40073.
2	259.987	270.255	4612.0	4599.8	522.45	0.65	4.96	4549.1	13.88	0.9047	39899.
3	279.968	280.236	4524.1	4512.9	522.34	0.68	5.09	4463.5	13.88	0.9160	39943.
4	289.990	290.259	4438.1	4427.0	522.30	0.68	5.16	4378.1	13.88	0.9129	39888.
5	299.972	300.240	4353.0	4342.0	522.15	0.63	4.99	4293.7	13.89	0.8699	39291.
6	309.994	310.221	4281.6	4270.9	522.05	0.42	4.13	4223.6	13.90	0.7068	35955.
7	319.975	320.243	4219.3	4208.6	521.97	0.29	3.46	4163.2	13.93	0.5825	33603.
8	329.998	330.224	4168.5	4159.0	521.95	0.21	2.93	4113.3	13.90	0.4926	31177.
9	339.979	340.247	4125.4	4115.3	521.96	0.17	2.67	4070.7	13.90	0.4414	29789.
10	349.960	350.228	4085.3	4076.4	521.94	0.15	2.41	4031.2	13.98	0.4144	28855.
11	359.982	360.250	4053.7	4043.4	521.88	0.07	1.81	3999.3	14.00	0.2817	26095.
12	369.963	370.231	4026.7	4016.9	521.82	0.03	1.26	3973.1	13.99	0.1778	23277.
13	379.986	380.254	4006.8	3996.8	521.81	0.0	0.54	3952.3	14.07	0.0007	20023.
14	389.967	390.235	3990.0	3980.4	521.95	0.0	0.48	3937.6	14.09	0.0007	16178.
15	399.989	400.257	3980.6	3971.1	521.95	0.0	0.12	3928.0	14.07	0.0007	16411.
16	409.971	410.239	3967.1	3957.5	521.96	0.0	0.62	3913.5	14.11	0.0007	19779.
17	419.993	420.220	3947.7	3937.6	521.95	0.02	1.11	389[illegible].7	14.09	0.1652	22627.
18	429.974	430.242	3920.2	3910.8	521.82	0.13	2.22	38[illegible].7	14.09	0.3707	27396.
19	439.955	440.223	3883.8	3875.7	521.58	0.16	2.33	3[illegible]1.6	14.11	0.4123	29016.
20	449.978	450.246	3847.5	3837.3	521.43	0.16	2.47	3794.4	14.12	0.4158	28841.
21	459.959	460.227	3808.9	3801.0	521.22	0.16	2.67	3757.3	14.12	0.4179	28828.
22	469.981	470.249	3769.1	3760.4	520.99	0.30	3.64	3717.2	14.12	0.5602	31866.
23	479.962	480.230	3716.6	3706.9	520.69	0.41	4.26	3664.4	14.14	0.6518	34197.
24	489.985	490.253	3663.7	3655.5	520.37	0.37	4.13	3612.2	14.13	0.6160	34917.
25	499.966	500.234	3616.1	3608.0	520.13	0.33	3.89	3567.1	14.16	0.5773	34334.
26	509.988	510.215	3569.5	3560.5	519.85	0.40	4.26	3519.5	14.13	0.6386	33648.
27	519.969	520.238	3516.3	3506.9	519.41	0.49	4.77	3466.3	14.15	0.6995	34591.
28	529.992	530.219	3463.2	3454.0	519.03	0.50	5.03	3413.8	14.21	0.7007	34722.
29	534.982	535.127	3435.8	3426.3	518.72	0.60	5.84	3386.5	14.21	0.8151	36638.

LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 11A
TEST DATE 6-30-82

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TEST DURATION, SEC 370.00

H Y B R I D B E A R I N G D A T A
PUMP - END (PAGE 1)

TIME SLICE NO	PUMP BRG SUPPLY U/S PRESS (PSIA)	PUMP BRG SUPPLY TEMP (DEG R)	PUMP BRG SUPPLY D/S ORIF PRESS (PSIA)	PUMP BRG SUPPLY ORIF DP (PSID)	PUMP BRG SUPPLY MANIF PRESS (PSIA)	--- PUMP BRG PAD PRESSURES --- 3.00 OCLOCK (PSIA)	9.00 OCLOCK (PSIA)	6.30 OCLOCK (PSIA)
1	431.0	84.4	411.4	22.0	421.7	194.5	196.5	16.7
2	428.6	76.4	409.4	22.7	419.7	197.8	200.2	16.2
3	432.5	72.9	411.9	23.1	421.7	200.8	202.6	15.1
4	432.4	71.3	411.5	22.7	421.7	202.0	203.5	14.8
5	431.0	70.5	409.5	21.2	420.0	200.4	201.9	14.3
6	387.3	69.5	373.1	14.7	383.5	187.2	188.2	14.6
7	374.4	69.3	365.1	9.2	375.0	189.6	192.4	16.1
8	337.8	68.5	331.0	6.9	340.7	172.5	174.4	18.3
9	328.4	68.4	321.1	6.0	331.7	166.0	167.7	18.1
10	315.0	68.0	306.7	6.9	316.7	151.7	152.3	16.2
11	294.7	67.3	287.9	5.3	298.1	139.4	140.1	16.4
12	278.3	66.8	273.4	3.1	283.8	139.5	140.5	16.5
13	261.5	66.2	257.8	2.2	268.1	130.8	131.7	16.7
14	242.6	65.4	240.3	0.8	250.2	125.7	125.8	16.2
15	239.3	65.4	236.5	0.7	246.6	127.3	127.1	16.2
16	255.4	66.6	251.9	1.7	261.8	130.1	130.9	16.5
17	271.1	67.7	266.8	2.7	277.0	135.7	136.6	16.4
18	307.7	69.7	301.2	3.9	311.4	155.0	155.5	16.5
19	318.8	69.8	310.6	5.8	321.0	155.6	157.0	16.2
20	197.0	62.7	197.8	0.0	207.6	125.3	121.5	16.3
21	192.9	62.7	194.4	0.0	204.3	134.5	131.1	16.7
22	216.6	64.1	216.4	0.0	226.7	139.8	137.2	16.7
23	245.4	65.6	242.7	1.0	252.5	135.9	133.5	16.5
24	253.1	66.0	249.9	1.3	260.3	139.4	137.6	16.5
25	248.6	65.5	245.7	0.5	256.8	137.4	136.2	16.5
26	240.2	64.8	238.6	0.0	248.9	133.0	130.2	16.6
27	246.3	65.1	244.7	0.0	255.5	139.3	137.2	16.7
28	246.0	65.1	244.6	0.0	255.0	138.8	136.8	16.6
29	257.3	65.8	254.6	0.0	265.4	141.6	139.6	16.6

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

PAGE 11. 7

RUN NUMBER 11A
TEST DATE 6-30-82

PROCESSING DATE 7-01-82
TEST DURATION, SEC 370.00

H Y B R I D   B E A R I N G   D A T A
PUMP - END (PAGE 2)

TIME SLICE NO	PUMP BRG SUMP PRESSURE (PSIA)	PUMP BRG SUMP OUT PRESSURE (PSIA)	PUMP BRG SUMP OUT TEMP (DEG R)	SHAFT SPEED (RPM)	CARTRIDGE SPEED (RPM)	PUMP BRG FLOW (LB/SEC)	LH2 DENSITY AT ORIF (PCF)	AVERAGE PAD PRESSURE (PSIA)	PUMP BRG PRESSURE RATIO
1	106.5	51.9	45.5	40073.	40032.	0.0613	1.3460	195.5	0.2824
2	106.3	52.9	45.6	39838.	39907.	0.0720	1.7954	199.0	0.2957
3	106.1	53.7	45.7	39943.	39953.	0.0799	2.1772	201.7	0.3028
4	106.2	54.3	45.8	39898.	39894.	0.0825	2.3653	202.7	0.3059
5	106.4	54.7	45.9	39791.	37243.	0.0814	2.4582	201.2	0.3074
6	106.8	53.6	45.7	35955.	35955.	0.0658	2.3128	187.7	0.2974
7	107.6	53.3	45.7	33603.	31009.	0.0511	2.2374	191.0	0.3119
8	108.1	53.4	45.7	31177.	28036.	0.0421	2.0272	173.5	0.2810
9	108.4	53.6	45.7	29949.	27975.	0.0385	1.9558	166.8	0.2615
10	107.5	52.8	45.6	28955.	28845.	0.0406	1.9666	152.0	0.2128
11	106.7	52.5	45.6	26085.	26049.	0.0343	1.7384	139.7	0.1725
12	107.5	52.6	45.6	23277.	23283.	0.0251	1.5921	140.0	0.1846
13	108.5	52.9	45.6	20023.	19913.	0.0201	1.4609	131.3	0.1476
14	108.5	53.0	45.6	16179.	16132.	0.0112	1.3165	125.8	0.1215
15	111.2	54.0	45.8	16411.	16049.	0.0103	1.2782	127.2	0.1181
16	107.5	52.6	45.6	19779.	19759.	0.0168	1.3316	130.5	0.1499
17	109.9	52.6	45.6	22677.	22613.	0.0219	1.3827	136.2	0.1646
18	109.0	52.5	45.6	27346.	27373.	0.0277	1.5385	155.2	0.2324
19	108.4	52.7	45.6	29916.	29941.	0.0349	1.6391	156.3	0.2252
20	106.5	54.5	45.9	28841.	28791.	0.0	1.0231	123.4	0.1671
21	105.6	54.3	45.9	28828.	28739.	0.0	0.9758	132.3	0.2701
22	105.4	54.3	45.8	31866.	31839.	0.0	1.1360	138.5	0.2727
23	106.1	53.8	45.8	34197.	34154.	0.0127	1.3315	134.7	0.1955
24	107.2	54.0	45.8	34917.	34854.	0.0149	1.3748	138.5	0.2045
25	108.0	54.0	45.8	34334.	34306.	0.0090	1.3890	136.8	0.1936
26	104.7	52.9	45.6	33648.	33603.	0.0	1.3676	131.6	0.1863
27	104.6	53.3	45.5	34531.	34483.	0.0	1.4097	138.2	0.2227
28	105.1	53.6	45.7	34722.	34649.	0.0	1.4199	137.9	0.2179
29	105.9	54.0	45.8	36638.	36609.	0.0	1.4647	140.6	0.2174

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RUN NUMBER 11
TEST DATE 6-30-82

PROCESSING DATE 7-01-82
TEST DURATION, SEC 370.00

H Y B R I D   B E A R I N G   D A T A
PUMP - END (PAGE 3)

TIME SLICE NO	BRG DELTA P ORIFICE PSID	BRG DELTA P FILM PSID	BRG DELTA P TOTAL PSID	ORIFICE RESISTANCE SEC**2/ LB-IN**2	FLUID FILM RESISTANCE SEC**2/ LB-IN**2	POISEUILLE RENOLDS NO	COUETTE RENOLDS NO	LAMBDA BRG NO	TORQUE FLUID FILM (TEMP) IN-LBS
1	225.2	89.0	315.2	60159.7	23669.8	45555083.	12118.	0.00347	-29.2471
2	220.7	92.7	313.4	42615.4	17891.5	58847293.	14885.	0.00330	-27.2805
3	220.0	95.6	315.6	34488.8	14976.9	66636461.	16500.	0.00323	-25.3376
4	219.0	96.5	315.5	32137.1	14164.7	70644874.	17312.	0.00320	-23.8793
5	218.8	94.8	313.6	33045.6	14327.0	72692959.	17428.	0.00312	-22.7153
6	195.8	80.9	276.7	45265.3	18700.9	58885913.	14970.	0.00320	-20.3713
7	184.0	83.4	267.4	70505.1	31956.8	71303135.	14462.	0.00252	-18.5259
8	167.2	65.3	232.5	94399.1	36897.1	55357392.	11963.	0.00257	-17.6696
9	164.9	58.4	223.3	111080.9	39332.6	54149052.	11904.	0.00258	-16.5617
10	164.7	44.5	209.2	100108.1	27066.2	52581435.	12119.	0.00266	-17.4367
11	158.3	33.0	191.3	134320.0	27997.9	50332879.	10890.	0.00242	-16.7618
12	143.7	32.5	176.3	228700.6	51769.4	48510704.	9996.	0.00223	-14.1516
13	136.9	22.8	159.6	339675.9	56479.2	45306829.	8542.	0.00196	-13.6145
14	124.4	17.2	141.6	991107.6	137118.7	41912950.	7010.	0.00165	-9.6509
15	119.4	16.0	135.4	1120783.4	150081.7	40867545.	7121.	0.00167	-9.0455
16	131.3	23.0	154.2	462871.8	80974.7	42891841.	8310.	0.00199	-12.1344
17	140.8	28.1	168.9	293747.3	58713.5	44928132.	9352.	0.00221	-13.8629
18	156.[illegible]	47.3	203.4	202825.2	61394.3	49587432.	11164.	0.00257	-14.3825
19	164..	47.9	212.6	135377.6	39340.5	50974866.	11766.	0.00267	-16.6679
20	84.2	16.9	101.0	************	************	29600129.	12989.	0.00373	0.0
21	72.1	26.7	98.7	************	************	29425392.	13369.	0.00383	0.0
22	88.2	33.1	121.3	************	************	33542447.	14301.	0.00398	0.0
23	117.8	28.6	146.4	732454.0	177957.1	36867506.	14202.	0.00392	-5.1413
24	121.8	31.3	153.2	550903.0	141640.4	38203353.	14624.	0.00393	-5.8821
25	120.0	28.8	148.8	1473982.0	353761.5	38128433.	14644.	0.00388	-3.5630
26	117.4	26.9	144.3	************	************	37098104.	14158.	0.00386	0.0
27	117.2	33.6	150.8	************	************	38544946.	14702.	0.00393	0.0
28	117.2	32.7	149.9	************	************	38324915.	14789.	0.00396	0.0
29	124.9	34.7	159.5	************	************	39168307.	15371.	0.00412	0.0

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MK49-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

PAGE 11. 2

RUN NUMBER 11A
TEST DATE 6-30-82

PROCESSING DATE 7-01-82
TEST DURATION, SEC 370.00

H Y B R I D   B E A R I N G   D A T A
PUMP AND TURBINE END (PAGE 4)

	- - - - - - - PUMP - - - - - -			- - - - - - - - - - - - - TURBINE - - - - - - - - - - - - - -					
TIME SLICE NO	HS BRG CLEARANCE RADIAL IN	VISCOSITY PUMP BRG LB-HR/FT**2 * E10	CSUBP PUMP BRG BTU/ LB-R	HS BRG CLEARANCE RADIAL IN	VISCOSITY TURB BRG LB-HR/FT**2 * E10	CSUBP TURB BRG BTU/ LB-R	POISEUILLE RENOLDS NO	COUETTE RENOLDS NO	LAMBDA TURB NO
1	0.00222	0.15070	3.2174	0.00246	0.24568	4.3371	181255473.	4.	0.0000
2	0.00222	0.14308	3.6276	0.00246	0.27807	4.2506	186734353.	14.	0.0000
3	0.00222	0.14082	3.9963	0.00246	0.31424	3.9888	186835270.	33.	0.0000
4	0.00222	0.13966	4.2300	0.00246	0.33721	3.8339	185599746.	15.	0.0000
5	0.00223	0.13886	4.3341	0.00246	0.34600	3.7641	188350071.	25.	0.0000
6	0.00226	0.14616	4.2319	0.00246	0.31811	4.0738	162572597.	52.	0.0000
7	0.00231	0.13605	4.3336	0.00246	0.30407	4.2622	150292256.	36.	0.0000
8	0.00233	0.14241	4.0913	0.00246	0.26722	4.8100	126262746.	32.	0.0000
9	0.00233	0.13945	3.9852	0.00246	0.25173	5.1024	119476855.	30.	0.0000
10	0.00233	0.13206	3.7632	0.00246	0.23547	5.5009	110991475.	29.	0.0000
11	0.00235	0.12791	3.6325	0.00246	0.21369	6.1128	104604394.	27.	0.0000
12	0.00237	0.12766	3.6787	0.00246	0.19435	6.8355	97901536.	26.	0.0000
13	0.00239	0.12589	3.5972	0.00246	0.17643	7.5543	93213965.	24.	0.0000
14	0.00241	0.12439	3.5728	0.00246	0.15656	8.2725	83903631.	22.	0.0000
15	0.00241	0.12459	3.6003	0.00246	0.15342	8.1385	72543626.	22.	0.0000
16	0.00239	0.12608	3.5473	0.00246	0.16604	7.6271	84201158.	23.	0.0000
17	0.00237	0.12772	3.5405	0.00246	0.18122	6.9527	92747766.	24.	0.0000
18	0.00234	0.13349	3.6480	0.00246	0.20446	6.0528	107802964.	27.	0.0000
19	0.00233	0.13386	3.6555	0.00246	0.21958	5.6232	118925546.	28.	0.0000
20	0.00233	0.12171	3.8139	0.00246	0.20394	6.5757	84098849.	26.	0.0000
21	0.00233	0.12340	4.0362	0.00246	0.20057	6.8474	76057651.	26.	0.0000
22	0.00230	0.12550	3.9865	0.00246	0.22060	6.1005	87025397.	28.	0.0000
23	0.00229	0.12596	3.7126	0.00246	0.24232	5.3207	107527839.	30.	0.0000
24	0.00227	0.12687	3.7351	0.00246	0.25329	5.0564	114604065.	32.	0.0000
25	0.00228	0.12622	3.7626	0.00246	0.25667	5.0145	115190165.	32.	0.0000
26	0.00229	0.12487	3.7364	0.00246	0.24587	5.2714	109798092.	31.	0.0000
27	0.00228	0.12621	3.8321	0.00246	0.24653	5.3464	102506079.	30.	0.0000
28	0.00228	0.12712	3.8269	0.00246	0.24640	5.3652	100789497.	30.	0.0000
29	0.00226	0.12705	3.7983	0.00246	0.25495	5.1627	103739681.	32.	0.0000

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 11[illegible]
TEST DATE 6-30-82

PROCESSING DATE 7-01-82
TEST DURATION, SEC 370.00

H Y B R I D B E A R I N G D A T A
TURBINE END (PAGE 1)

TIME SLICE NO	TURB BRG SUPPLY U/S PRESS (PSIA)	TURB BRG SUPPLY U/S TEMP (DEG R)	TURB BRG SUPPLY D/S ORIF PRESS (PSIA)	TURB BRG SUPPLY ORIF DP (PSID)	TURB BRG SUPPLY MANIF PRESS (PSIA)	TURB BRG DISCH PRESS (PSIA)	TURB BRG SUMP PRESS (PSIA)	TURBINE BRG DISCHARGE LINE PRESS (PSIA)	TURBINE BRG DISCHARGE LINE TEMP (DEG R)
1	1137.0	95.3	1093.0	54.0	1017.1	488.2	461.3	121.2	54.1
2	1151.6	84.5	1102.8	62.3	1019.0	484.9	457.0	126.8	54.6
3	1162.8	78.1	1115.1	61.7	1025.8	484.9	457.0	130.5	54.9
4	1165.7	75.0	1117.3	61.7	1025.7	482.0	455.5	132.2	55.1
5	1166.4	73.6	1117.4	63.0	1023.5	472.3	445.9	132.5	55.1
6	1007.1	73.7	965.9	50.8	887.3	412.0	386.9	116.8	53.6
7	940.8	73.0	902.2	48.2	830.5	380.5	355.2	106.5	52.7
8	806.8	74.5	773.6	39.2	714.3	342.5	319.1	95.8	51.6
9	757.6	74.8	726.4	36.6	672.3	326.1	301.8	91.7	51.1
10	702.8	75.2	673.6	34.4	625.4	309.7	285.9	88.1	50.7
11	633.3	75.1	606.5	32.2	562.2	275.2	252.0	79.2	49.7
12	558.6	74.5	537.1	27.7	500.5	244.4	221.1	70.8	48.6
13	497.5	73.8	477.6	21.7	445.8	213.5	190.4	62.8	47.5
14	414.6	72.5	398.9	15.4	375.2	175.3	151.9	53.5	46.0
15	385.4	72.7	370.8	13.8	350.5	179.9	157.7	54.8	46.3
16	453.0	74.2	435.5	17.5	410.0	208.1	184.3	61.3	47.3
17	522.5	76.1	502.5	23.3	471.4	236.7	213.8	68.0	48.2
18	640.4	78.4	615.2	30.9	576.3	290.4	266.9	80.7	49.8
19	711.4	78.6	683.3	34.7	637.0	313.4	289.3	85.7	50.4
20	574.8	76.3	554.1	25.9	520.7	302.1	277.9	87.9	50.6
21	543.6	75.7	525.2	21.5	495.0	299.2	275.8	86.7	50.5
22	629.7	76.7	608.0	30.7	571.5	339.1	314.2	99.9	51.9
23	756.5	78.2	726.5	37.6	679.1	383.0	357.3	97.0	51.7
24	811.3	78.6	779.5	40.4	727.3	407.6	382.4	111.6	53.2
25	812.0	77.8	779.3	40.1	726.3	404.4	378.8	106.4	52.6
26	754.1	77.0	724.2	36.9	675.0	368.4	343.2	106.6	52.6
27	736.2	76.7	707.6	36.5	661.4	376.1	350.4	103.5	52.4
28	733.6	76.8	705.1	36.2	659.4	378.3	353.9	106.9	52.8
29	768.3	77.1	741.5	35.9	693.5	405.4	379.7	116.8	53.7

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MK48-F

LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 11A
TEST DATE 6-30-82

PROCESSING DATE 7-01-82
TEST DURATION, SEC 370.00

H Y B R I D B E A R I N G D A T A
TURBINE END (PAGE 2)

TIME SLICE NO	SHAFT SPEED (RPM)	TURBINE CARTRIDGE SPEED (RPM)	TURBINE H/S BRG FLOW (LB/SEC)	LH2 DENSITY AT ORIF (PCF)	TURB BRG SUPPLY MANIF PRESS (PSIA)	TURB BRG DISCH PRESS (PSIA)	TURB BRG SUMP PRESS (PSIA)	HYDROSTATIC BEARING DELTA PRESS (PSID)
1	40073.	6.	0.1914	2.706	1017.1	488.2	461.3	555.88
2	39858.	18.	0.2233	3.187	1019.0	484.9	457.0	562.03
3	39943.	38.	0.2320	3.476	1025.8	494.9	457.0	568.89
4	39888.	16.	0.2365	3.613	1025.7	482.0	455.5	570.22
5	39291.	26.	0.2409	3.673	1024.5	472.3	445.9	577.59
6	35955.	60.	0.2116	3.513	887.3	412.9	386.9	500.35
7	33603.	45.	0.2036	3.425	830.5	380.5	355.2	475.31
8	31177.	45.	0.1777	3.204	714.3	342.5	319.1	395.20
9	29588.	45.	0.1689	3.101	672.3	326.1	301.8	370.52
10	28855.	85.	0.1600	2.965	625.4	309.7	285.9	339.43
11	26085.	45.	0.1504	2.801	562.2	275.2	252.0	310.20
12	23277.	45.	0.1348	2.618	500.5	244.4	221.1	279.39
13	20023.	45.	0.1155	2.430	445.8	213.5	190.4	255.33
14	16178.	45.	0.0993	2.107	375.2	175.3	151.9	223.33
15	16411.	45.	0.0817	1.932	350.5	179.9	157.7	192.74
16	19779.	45.	0.0973	2.157	410.0	208.1	194.3	225.69
17	22627.	45.	0.1163	2.318	471.4	236.7	213.8	257.61
18	27396.	45.	0.1411	2.566	576.3	290.4	266.9	309.43
19	29016.	45.	0.1547	2.752	537.7	313.4	289.3	347.75
20	28841.	45.	0.1277	2.514	520.7	302.1	277.9	247.75
21	29878.	45.	0.1200	2.446	495.0	299.7	275.8	219.18
22	31866.	45.	0.1433	2.665	571.5	339.1	314.2	257.35
23	34197.	45.	0.1650	2.885	670.1	383.0	357.3	321.80
24	34917.	45.	0.1734	2.969	727.3	407.6	382.4	344.92
25	34334.	45.	0.1742	3.018	726.3	404.4	378.8	347.46
26	33648.	45.	0.1655	2.958	675.0	368.4	343.2	331.76
27	34591.	45.	0.1642	2.938	651.6	376.1	350.4	311.03
28	34772.	45.	0.1631	2.929	650.6	378.3	353.0	305.59
29	36638.	45.	0.1633	2.976	6[illegible].5	405.4	379.7	313.80

MK49-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 11B
TEST DATE 6-30-82

RERUN
9/8/82

PROCESSING DATE 7-07-82
TEST DURATION, SEC 370.00

COMMENTS . . .
TEST 11B
PID109(IND INL P) BAD. USED PID97

AMBIENT PRESSURE		13.8000
LO2 VENTURI (GG)		
P/N V160248-SGR	UPSTREAM DIAMETER	0.0
S/N 8871	THROAT DIAMETER	0.0
	THROAT CD	0.0
GH2 VENTURI (TURB)		
P/N VP031209-SGR	UPSTREAM DIAMETER	2.3000
S/N 9731	THROAT DIAMETER	1.3085
	THROAT CD	0.9873
LH2 VENTURI (GG)		
P/N V320471-SGR	UPSTREAM DIAMETER	0.0
S/N 8873	THROAT DIAMETER	0.0
	THROAT CD	0.0
LH2 VENTURI (PUMP DISCH)		
P/N V320709-SGR	UPSTREAM DIAMETER	1.6890
S/N 8874	THROAT DIAMETER	0.7090
	THROAT CD	0.9760

TURBINE SYSTEM EFF. AREA		0.70470
TURBINE EXHAUST ORIFICE	4 EACH	0.31200
	4 EACH	0.32500
	1 EACH	0.30800
	4 EACH	0.37500
TURBINE EXHAUST EFF. AREA		1.03600

HYDROSTATIC BEARING SUPPLY SYSTEM
TURBINE INLET DUCT DIA 0.334 ORIFICE DIA 0.194
PUMP INLET DUCT DIA 0.492 ORIFICE DIA 0.175

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 11[illegible]
TEST DATE 6-30-82

PROCESSING DATE 7-07-82
TEST DURATION, SEC 370.00

G A S E O U S H Y D R O G E N T U R B I N E D R I V E P A R A M E T E R S

TIME SLICE (-)	BEGIN TIME (SEC)	END TIME (SEC)	REG U/S PR (PSIA)	VENTURI U/S PR (PSIA)	VENTURI U/S TEMP (DEG R)	VENTURI DELTA PR (PSID)	SPIN VALVE POSN	SPIN VALVE U/S PR (PSIA)	FAC DUCT PR (PSIA)	TURB GH2 FLOW (LB/SEC)	SPEED (RPM)
1	537.498	537.643	3418.6	3410.6	518.62	0.75	6.98	3369.6	14.21	0.9618	39419.
2	539.973	540.159	3401.3	3392.4	518.43	1.05	7.34	3350.7	14.24	1.0103	40239.
3	542.489	542.633	3380.[illegible]	3371.1	518.11	1.2[illegible]	7.97	3329.9	14.21	1.0860	41[illegible]8.
4	544.964	545.149	3357.5	3350.0	517.91	1.42	8.59	3307.9	14.20	1.1649	43257.
5	547.479	547.624	3336.6	3329.2	517.52	1.33	8.29	3287.7	14.21	1.1117	42081.
6	549.995	550.140	3312.9	3304.9	517.31	1.71	9.63	3263.2	14.24	1.2718	44754.
7	552.470	552.656	3286.5	3278.8	516.91	2.12	10.82	3236.4	14.24	1.4103	46914.
8	554.996	555.130	3259.2	3251.6	516.52	2.53	11.91	3208.5	14.23	1.5354	48595.
9	557.461	557.646	3230.0	3220.9	516.05	[illegible].02	13.08	3177.2	14.[illegible]	1.6701	50461.
10	559.977	560.121	3197.4	3189.3	515.63	3.10	13.37	3144.6	14.54	1.6844	50689.
11	562.492	562.637	3165.8	3157.0	515.10	3.13	13.39	3113.[illegible]	14.54	1.6762	50641.
12	564.967	565.153	3138.1	3130.0	514.81	2.63	11.93	3087.7	14.26	1.4789	47914.
13	567.433	567.627	3110.5	3102.5	514.51	2.45	12.05	3060.9	14.31	1.4835	47986.
14	569.958	570.143	3083.6	3075.5	514.18	2.48	12.16	3034.3	14.29	1.4845	48000.
15	572.474	572.618	3063.[illegible]	3055.0	514.[illegible]7	1.48	9.23	3015.3	14.33	1.1412	42844.
16	574.990	575.134	3041.5	3035.3	513.88	1.31	8.72	2997.3	14.29	1.0729	41648.
17	577.464	577.650	3023.9	3016.8	513.87	1.21	8.41	2979.6	14.40	1.0271	40965.
18	579.980	580.124	3005.3	2999.8	513.77	1.12	8.23	2961.7	14.28	0.9871	40098.
19	582.455	582.640	2986.2	2980.3	513.52	1.60	9.87	2942.0	14.36	1.1740	43262.
20	584.971	585.156	2964.5	2958.1	513.17	2.10	11.36	2919.2	14.42	1.3400	45588.
21	587.487	587.631	2943.3	2932.7	512.63	2.70	13.04	2892.0	14.41	1.5147	48244.
22	589.961	590.147	2910.9	2903.4	512.[illegible]	3.13	14.30	2862.0	14.54	1.6392	49966.
23	592.477	592.622	2881.2	2873.1	511.2[illegible]	3.73	15.55	2830.4	14.84	1.7624	51488.
24	594.993	595.137	2846.7	2839.8	510.5[illegible]	4.53	17.22	2795.2	15.61	1.9276	53729.
25	597.468	597.653	2813.9	2805.8	509.84	4.43	17.19	2762.5	15.43	1.8952	53340.
26	599.984	600.128	2780.3	2772.9	509.23	4.61	17.66	2729.1	15.69	1.9294	53675.
27	602.458	602.644	2747.3	2742.5	508.74	0.0	-0.65	2703.6	14.41	0.0003	33852.
28	604.974	605.117	2756.5	2751.2	510.17	0.0	-0.49	215.9	14.44	0.0003	2654.

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RUN NUMBER 118
TEST DATE 6-30-82

PROCESSING DATE 7-07-82
TEST DURATION, SEC 370.00

H Y B R I D B E A R I N G D A T A
PUMP - END (PAGE 1)

TIME SLICE NO	PUMP BRG SUPPLY U/S PRESS (PSIA)	PUMP BRG SUPPLY TEMP (DEG R)	PUMP BRG SUPPLY D/S ORIF PRESS (PSIA)	PUMP BRG SUPPLY ORIF DP (PSID)	PUMP BRG SUPPLY MANIF PRESS (PSIA)	--- PUMP BRG PAD PRESSURES --- 3.00 OCLOCK (PSIA)	9.00 OCLOCK (PSIA)	6.30 OCLOCK (PSIA)
1	288.8	67.3	283.8	1.8	294.8	153.2	152.3	16.7
2	300.0	67.8	293.9	2.4	304.8	157.0	156.1	16.6
3	318.9	68.5	310.5	4.2	321.5	163.0	161.8	16.6
4	340.4	69.4	330.1	5.7	340.8	172.7	171.9	16.6
5	326.8	68.8	317.9	4.9	328.6	166.7	164.7	16.6
6	357.0	69.9	344.5	6.9	355.9	180.4	180.2	16.6
7	385.2	70.6	372.0	8.2	384.0	196.3	196.7	16.5
8	405.4	71.0	390.2	9.8	401.8	201.2	207.8	16.6
9	434.6	71.5	416.3	12.1	428.8	221.7	224.0	16.2
10	441.2	71.3	422.6	12.9	434.1	223.2	226.5	16.2
11	440.2	71.1	421.5	12.7	433.3	223.3	225.6	16.2
12	403.4	70.1	387.3	9.4	398.8	203.5	205.0	16.2
13	399.8	69.9	384.3	9.4	396.1	202.8	205.0	16.2
14	404.1	69.9	388.1	9.4	399.7	204.9	207.0	16.1
15	340.1	68.0	330.3	4.2	341.4	173.4	171.7	16.2
16	321.9	67.4	313.7	2.5	325.3	164.3	163.6	16.2
17	313.6	67.1	306.6	1.4	318.2	161.4	159.4	16.2
18	302.7	66.7	296.9	0.0	309.3	158.4	157.1	16.2
19	335.5	67.9	326.5	2.9	337.7	173.1	171.9	16.1
20	361.7	68.6	349.9	4.8	361.5	185.3	185.8	16.1
21	400.4	69.6	385.3	7.4	397.1	205.2	206.4	16.2
22	427.1	70.2	409.4	9.9	421.7	218.5	219.9	16.2
23	450.8	70.7	430.5	12.0	442.6	228.7	229.8	16.0
24	485.7	71.6	467.7	9.4	479.6	257.3	260.8	16.1
25	468.7	71.3	451.2	10.0	463.6	246.6	248.7	16.1
26	481.3	71.4	460.0	12.8	472.9	248.2	250.2	16.0
27	379.8	69.4	379.5	0.0	388.0	207.2	207.1	16.2
28	99.5	67.4	110.5	0.0	120.3	111.2	109.1	16.2

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

PAGE 11. 7

RUN NUMBER 118
TEST DATE 6-30-82

PROCESSING DATE 7-07-82
TEST DURATION, SEC 370.00

H Y B R I D B E A R I N G D A T A
PUMP - END (PAGE 2)

TIME SLICE NO	PUMP BRG SUMP PRESSURE (PSIA)	PUMP BRG SUMP OUT PRESSURE (PSIA)	PUMP BRG SUMP OUT TEMP (DEG R)	SHAFT SPEED (RPM)	CARTRIDGE SPEED (RPM)	PUMP BRG FLOW (LB/SEC)	LH2 DENSITY AT ORIF (PCF)	AVERAGE PAD PRESSURE (PSIA)	PUMP BRG PRESSURE RATIO
1	105.5	53.4	45.7	39419.	39362.	0.0195	1.6516	152.8	0.2498
2	104.6	53.5	45.7	40239.	40194.	0.0226	1.7118	156.5	0.2594
3	103.6	53.8	45.7	41738.	41666.	0.0310	1.8162	162.4	0.2698
4	103.6	53.6	45.7	43257.	43148.	0.0371	1.9106	172.3	0.2897
5	105.7	54.5	45.9	42081.	42013.	0.0340	1.8617	165.7	0.2694
6	104.2	54.6	45.9	44754.	44675.	0.0417	2.0000	180.3	0.3026
7	103.1	54.7	46.0	46914.	46813.	0.0471	2.1287	196.5	0.3325
8	101.9	54.6	45.9	48599.	48503.	0.0526	2.2351	207.5	0.3521
9	103.8	56.2	46.2	50461.	50315.	0.0607	2.3619	222.8	0.3663
10	103.3	56.2	46.2	50683.	50561.	0.0629	2.4153	224.9	0.3674
11	102.6	55.7	46.1	50641.	50474.	0.0626	2.4369	224.5	0.3687
12	102.3	54.7	46.0	47914.	47808.	0.0530	2.3411	204.3	0.3439
13	103.8	55.1	46.0	47986.	47881.	0.0528	2.3472	203.9	0.3424
14	104.1	55.3	46.0	48006.	47878.	0.0533	2.3826	206.0	0.3446
15	104.2	54.1	45.8	42844.	42710.	0.0337	2.1445	172.6	0.2884
16	103.7	54.3	45.8	41649.	41530.	0.0256	2.0614	163.9	0.2718
17	104.4	53.6	45.7	40965.	40820.	0.0190	2.0229	160.4	0.2619
18	105.7	54.3	45.9	40098.	39999.	0.0	1.9535	157.7	0.2554
19	104.3	54.3	45.9	43262.	43143.	0.0277	2.1233	172.5	0.2920
20	103.1	54.5	45.9	45588.	45493.	0.0374	2.2432	185.5	0.3190
21	102.0	54.6	45.9	48744.	48119.	0.0475	2.3942	205.9	0.3517
22	103.9	56.2	46.2	49766.	49803.	0.0557	2.4770	219.2	0.3627
23	102.6	56.6	46.2	51488.	51322.	0.0623	2.5503	229.2	0.3725
24	101.5	56.5	46.2	53729.	53535.	0.0558	2.6138	259.1	0.4167
25	100.9	56.7	46.2	53360.	53157.	0.0571	2.5094	247.6	0.4047
26	103.1	57.6	46.3	51675.	51577.	0.0653	2.6158	249.2	0.3950
27	114.1	87.5	49.7	33852.	47072.	0.0	2.2746	207.1	0.3335
28	197.9	54.8	46.9	2654.	1636.	0.0	0.3212	110.1	0.1821

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 118
TEST DATE 6-30-82

PROCESSING DATE 7-07-82
TEST DURATION, SEC 370.00

H Y B R I D B E A R I N G D A T A
PUMP - END (PAGE 3)

TIME SLICE NO	BRG DELTA P ORIFICE PSID	BRG DELTA P FILM PSID	BRG DELTA P TOTAL PSID	ORIFICE RESISTANCE SEC**2/ LB-IN**2	FLUID FILM RESISTANCE SEC**2/ LB-IN**2	POISEUILLE RENOLDS NO	COUETTE RENOLDS NO	LAMBDA BRG NO	TORQUE FLUID FILM (TEMP) IN-LBS
1	142.0	47.3	189.4	373980.6	124554.0	41993391.	15962.	0.00426	-6.4196
2	148.2	51.9	200.1	289658.9	101464.3	42547132.	16001.	0.00431	-7.2527
3	159.1	58.8	217.9	165211.0	61033.3	43809526.	16230.	0.00438	-9.4685
4	168.5	68.7	237.3	122199.2	49851.2	45559404.	16688.	0.00445	-10.8542
5	162.9	60.1	222.9	140519.8	51809.7	44565242.	16481.	0.00438	-10.1718
6	175.5	76.2	251.7	100823.1	43745.7	47040730.	17347.	0.00455	-11.5537
7	187.5	93.4	281.0	84565.3	42125.7	56398989.	19390.	0.00439	-12.1103
8	194.3	105.6	299.9	70087.4	38096.2	58242170.	20185.	0.00451	-12.7738
9	206.0	119.1	325.1	56880.7	32874.0	61196366.	21320.	0.00461	-13.6410
10	209.3	121.5	330.8	52851.6	30678.3	62164526.	21527.	0.00460	-13.9106
11	208.8	121.9	330.7	53218.8	31082.3	62421146.	21540.	0.00460	-13.7188
12	194.5	101.9	296.4	69286.7	36312.3	59862321.	20351.	0.00441	-12.3546
13	192.2	100.1	292.3	68887.7	35866.4	59663313.	20602.	0.00444	-12.1888
14	193.8	101.9	295.7	68097.1	35807.1	60615296.	20754.	0.00442	-12.1534
15	168.8	68.4	237.2	148770.9	60281.3	45993962.	16904.	0.00446	-8.8871
16	161.3	60.2	221.6	246573.8	92035.4	45073325.	16573.	0.00437	-6.9963
17	157.9	56.0	213.9	435551.0	154525.5	44960792.	16477.	0.00430	-5.3323
18	151.6	52.0	203.6	************	************	44428588.	16442.	0.00425	0.0
19	165.2	68.1	233.3	214602.7	88529.4	44989674.	17081.	0.00458	-7.2363
20	176.0	82.4	258.4	128127.2	60008.5	46380113.	17784.	0.00478	-9.0043
21	191.3	103.8	295.1	84627.8	45907.7	60154807.	20788.	0.00448	-10.6572
22	202.5	115.3	317.8	65200.5	37112.4	62567214.	21745.	0.00457	-11.9006
23	213.3	126.6	340.0	54914.8	32600.5	64036463.	22281.	0.00466	-12.7824
24	220.5	157.5	378.1	70905.7	50654.2	65480251.	23418.	0.00492	-10.9555
25	215.9	146.8	362.7	66122.5	44944.3	64202148.	23052.	0.00490	-11.3695
26	223.8	146.1	369.8	52491.0	34270.5	65298981.	23370.	0.00488	-12.7392
27	180.9	93.0	273.9	************	************	60253179.	21713.	0.00444	0.0
28	10.2	2.3	12.5	************	************	3437038.	635.	0.00033	0.0

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MSAR-E
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 118
TEST DATE 6-30-82

PROCESSING DATE 7-07-82
TEST DURATION, SEC 370.00

HYBRID BEARING DATA
PUMP AND TURBINE (IP) (PAGE 4)

TIME SLICE NO	PUMP: HS BRG CLEARANCE RADIAL IN	PUMP: VISCOSITY PUMP BRG LB-HR/FT**2 * E10	PUMP: CSUBP PUMP BRG BTU/LB-R	TURBINE: HS BRG CLEARANCE RADIAL IN	TURBINE: VISCOSITY TURB BRG LB-HR/FT**2 * E10	TURBINE: CSUBP TURB BRG BTU/LB-R	TURBINE: POISEUILLE REYNOLDS NO	TURBINE: COUETTE REYNOLDS NO	TURBINE: LAMBDA TURB NO
1	0.00223	0.13240	3.8520	0.00247	0.28048	4.7387	111032376.	0.	0.0
2	0.00222	0.13450	3.8611	0.00247	0.29326	4.4994	126700133.	0.	0.0
3	0.00220	0.13710	3.8755	0.00247	0.30122	4.3033	139472836.	0.	0.0
4	0.00218	0.14035	3.9500	0.00246	0.31619	4.1099	149778910.	0.	0.0
5	0.00220	0.13837	3.9065	0.00246	0.31197	4.1319	154459947.	0.	0.0
6	0.00217	0.14238	4.0123	0.00247	0.32993	3.9484	169999629.	0.	0.0
7	0.00214	0.13797	4.2215	0.00246	0.34948	3.7976	164844605.	0.	0.0
8	0.00212	0.14539	4.3858	0.00246	0.36576	3.6949	162945969.	0.	0.0
9	0.00209	0.14414	4.6175	0.00246	0.37971	3.6164	159546707.	0.	0.0
10	0.00209	0.14461	4.6925	0.00246	0.38304	3.5921	158209400.	0.	0.0
11	0.00209	0.14450	4.7366	0.00246	0.38596	3.5757	157569054.	0.	0.0
12	0.00213	0.13928	4.4843	0.00246	0.38103	3.5784	169134306.	0.	0.0
13	0.00213	0.13916	4.5212	0.00246	0.38536	3.5595	168003455.	0.	0.0
14	0.00213	0.13360	4.5806	0.00246	0.39780	3.5467	164848874.	0.	0.0
15	0.00219	0.14287	4.1525	0.00247	0.36867	3.5994	154180789.	0.	0.0
16	0.00220	0.13895	4.0637	0.00246	0.35765	3.6913	185299506.	0.	0.0
17	0.00221	0.13706	4.0926	0.00246	0.34626	3.8202	174599541.	0.	0.0
18	0.00227	0.13557	4.0281	0.00247	0.32674	4.0381	157293716.	0.	0.0
19	0.00218	0.14302	4.1745	0.00247	0.34174	3.9216	149099395.	0.	0.0
20	0.00216	0.14790	4.3388	0.00247	0.35788	3.7749	157496652.	0.	0.0
21	0.00212	0.14952	4.6155	0.00246	0.38181	3.6061	156458508.	0.	0.0
22	0.00210	0.14298	4.8308	0.00246	0.39465	3.5294	159931530.	0.	0.0
23	0.00208	0.14560	4.9821	0.00246	0.37746	3.5136	152678805.	0.	0.0
24	0.00205	[illegible]	[illegible]	[illegible]	0.40368	3.4996	141274455.	0.	0.0
25	0.00206	0.15107	5.3236	[illegible]	0.40370	3.5092	[illegible]	0.	0.0
26	0.00205	[illegible]	5.3127	[illegible]	0.41320	3.4973	[illegible]	0.	0.0
27	0.00214	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.	0.0
28	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	10.7122	[illegible]	0.	0.0

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 11B
TEST DATE 6-30-82

PROCESSING DATE 7-07-82
TEST DURATION, SEC 370.00

HYBRID BEARING DATA
TURBINE END (PAGE 1)

TIME SLICE NO	TURB BRG SUPPLY U/S PRESS (PSIA)	TURB BRG SUPPLY U/S TEMP (DEG R)	TURB BRG SUPPLY D/S ORIF PRESS (PSIA)	TURB BRG SUPPLY ORIF DP (PSID)	TURB BRG SUPPLY MANIF PRESS (PSIA)	TURB BRG DISCH PRESS (PSIA)	TURB BRG SUMP PRESS (PSIA)	-- TURBINE BRG -- DISCHARGE PRESS (PSIA)	LINE TEMP (DEG R)
1	862.8	77.6	831.1	39.9	777.6	455.5	429.7	113.4	53.3
2	931.3	77.6	896.1	44.5	835.7	469.3	443.8	126.0	54.6
3	999.2	77.6	960.6	49.3	892.5	491.7	465.8	141.4	55.8
4	1073.3	77.5	1033.1	51.8	960.4	528.4	503.5	130.5	54.9
5	1066.4	77.4	1024.2	52.6	950.1	504.5	478.6	140.3	55.8
6	1142.3	77.3	1097.0	55.2	1017.4	550.8	522.8	154.0	56.7
7	1221.6	76.7	1175.1	59.0	1090.8	598.1	571.8	152.6	56.7
8	1267.9	75.9	1220.3	60.7	1132.8	632.8	606.6	154.9	56.8
9	1304.3	75.3	1256.8	62.1	1168.1	668.6	647.5	169.4	58.0
10	1306.1	74.8	1257.9	62.2	1170.6	672.3	646.4	172.2	58.2
11	1306.1	74.4	1257.6	62.4	1169.5	671.9	645.4	169.0	57.9
12	1297.3	74.0	1246.3	65.2	1153.3	621.7	596.5	154.8	56.8
13	1298.1	73.6	1248.0	64.8	1154.5	625.7	598.9	153.3	56.8
14	1297.7	73.3	1248.2	64.6	1154.7	626.8	601.0	151.6	56.6
15	1264.3	73.1	1209.3	68.6	1110.7	523.3	496.3	147.5	55.7
16	1199.8	73.3	1149.2	63.3	1056.0	506.7	490.6	138.9	55.7
17	1125.1	73.5	1077.8	58.4	993.2	488.8	462.1	129.7	54.7
18	1018.8	73.8	977.9	50.3	904.3	466.7	439.6	135.5	55.3
19	1068.6	73.8	1028.3	51.0	953.4	525.5	500.0	136.4	55.3
20	1141.9	73.7	1097.6	54.7	1018.5	568.3	542.9	145.0	56.1
21	1244.4	73.3	1197.4	60.2	1110.7	625.2	599.6	150.5	56.5
22	1303.9	73.0	1255.0	64.0	1164.7	656.9	630.4	168.7	57.9
23	1309.6	73.2	1262.1	64.0	1174.6	685.0	658.3	178.6	58.6
24	1320.2	73.4	1275.6	61.5	1192.9	737.4	711.7	177.3	58.5
25	1318.6	73.4	1271.8	62.4	1187.7	722.3	695.7	183.5	58.9
26	1319.5	73.3	1273.9	61.9	1191.4	732.1	703.5	186.9	59.1
27	1268.4	73.0	1210.0	73.5	1105.7	419.5	396.8	147.9	56.8
28	380.8	68.3	366.0	14.4	345.6	124.2	102.4	47.0	45.0

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 118
TEST DATE 6-30-82

PROCESSING DATE 7-07-82
TEST DURATION, SEC 370.00

H Y B R I D B E A R I N G D A T A
TURBINE END (PAGE 2)

TIME SLICE NO	SHAFT SPEED (RPM)	TURBINE CARTRIDGE SPEED (RPM)	TURBINE H/S BRG FLOW (LB/SEC)	LH2 DENSITY AT ORIF (PCF)	TURB BRG SUPPLY MANIF PRESS (PSIA)	TURB BRG DISCH PRESS (PSIA)	TURB BRG SUMP PRESS (PSIA)	HYDROSTATIC BEARING DELTA PRESS (PSID)
1	39419.	0.	0.1767	3.119	777.6	455.5	429.7	347.90
2	40239.	0.	0.1898	3.224	835.2	467.3	443.8	391.38
3	41738.	0.	0.2025	3.316	892.5	491.7	465.8	426.70
4	43257.	0.	0.2105	3.408	960.4	528.4	503.5	456.90
5	42081.	0.	0.2120	3.403	950.1	504.5	478.6	471.44
6	44754.	0.	0.2199	3.490	1017.4	550.8	522.8	494.59
7	46914.	0.	0.2307	3.593	1090.8	598.1	571.8	518.97
8	48599.	0.	0.2363	3.664	1132.8	632.8	606.6	526.19
9	50461.	0.	0.2408	3.718	1168.1	668.6	642.5	525.57
10	50689.	0.	0.2415	3.738	1170.6	672.3	646.6	524.20
11	50641.	0.	0.2424	3.754	1169.5	671.9	645.4	524.00
12	47914.	0.	0.2482	3.764	1153.3	621.7	596.5	556.80
13	47986.	0.	0.2480	3.780	1154.5	625.7	598.9	555.63
14	48000.	0.	0.2479	3.790	1154.7	626.8	601.0	553.64
15	42844.	0.	0.2548	3.772	1110.7	523.3	496.3	614.35
16	41648.	0.	0.2429	3.714	1056.0	506.7	480.6	575.36
17	40965.	0.	0.2309	3.637	993.2	488.8	462.1	531.05
18	40098.	0.	0.2108	3.519	904.3	466.7	439.6	464.72
19	43262.	0.	0.2137	3.569	953.4	525.5	500.0	453.38
20	45588.	0.	0.2236	3.645	1018.5	568.3	542.9	475.67
21	48244.	0.	0.2380	3.750	1119.7	625.2	599.6	511.09
22	45966.	0.	0.2472	3.806	1164.7	656.9	630.4	534.28
23	51488.	0.	0.2472	3.805	1174.6	685.0	658.3	516.30
24	53729.	0.	0.2424	3.805	1192.9	737.4	711.7	481.25
25	53340.	0.	0.2439	3.801	1187.7	722.3	695.7	492.06
26	53675.	0.	0.2433	3.808	1191.4	732.1	703.5	487.89
27	33852.	0.	0.2640	3.778	1105.7	419.5	396.8	708.88
28	2654.	0.	0.0942	2.457	345.6	124.2	102.4	243.13

ORIGINAL PAGE IS
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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 12A
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COMMENTS . . .
TEST 12A

AMBIENT PRESSURE		13.8000
LO2 VENTURI (GG)		
P/N V160248-SGR	UPSTREAM DIAMETER	0.0
S/N 8871	THROAT DIAMETER	0.0
	THROAT CD	0.0
GH2 VENTURI (TURB)		
P/N VP031200-SGR	UPSTREAM DIAMETER	2.3000
S/N 9731	THROAT DIAMETER	1.3085
	THROAT CD	0.9873
LH2 VENTURI (GG)		
P/N V320471-SGR	UPSTREAM DIAMETER	0.0
S/N 8873	THROAT DIAMETER	0.0
	THROAT CD	0.0
LH2 VENTURI (PUMP DISCH)		
P/N V320709-SGR	UPSTREAM DIAMETER	1.6890
S/N 8874	THROAT DIAMETER	0.7090
	THROAT CD	0.9760

TURBINE SYSTEM EFF. AREA		0.70470
TURBINE EXHAUST ORIFICE	4 EACH	0.31200
	4 EACH	0.32500
	1 EACH	0.30000
	4 EACH	0.37500
	4 EACH	0.31250
TURBINE EXHAUST EFF. AREA		1.28100

HYDROSTATIC BEARING SUPPLY SYSTEM
TURBINE INLET DUCT DIA 0.334 ORIFICE DIA 0.194
PUMP INLET DUCT DIA 0.402 ORIFICE DIA 0.175

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G A S E O U S   H Y D R O G E N   T U R B I N E   D R I V E   P A R A M E T E R S

TIME SLICE NO	BEGIN TIME (SEC)	END TIME (SEC)	REG U/S PR (PSIA)	VENTURI U/S PR (PSIA)	VENTURI U/S TEMP (DEG R)	VENTURI DELTA PR (PSID)	SPIN VALVE POSN	SPIN VALVE U/S PR (PSIA)	FAC DUCT PR (PSIA)	TURB GH2 FLOW (LB/SEC)	SPEED (RPM)
1	189.972	190.150	4925.2	4913.3	543.79	0.0	0.10	4904.0	13.92	0.0	11263.
2	194.963	195.148	4913.4	4901.6	540.64	0.11	1.02	4892.3	13.94	0.3678	30765.
3	199.995	200.139	4878.8	4868.0	541.60	0.43	3.01	4856.8	13.91	0.7281	40076.
4	204.985	205.130	4841.6	4829.5	542.49	0.42	3.64	4819.4	13.93	0.7119	39980.
5	209.976	210.120	4805.3	4793.5	543.92	0.42	3.64	4783.4	13.93	0.7103	39998.
6	214.966	215.152	4770.4	4758.0	544.67	0.42	3.76	4747.6	13.94	0.7077	40028.
7	219.998	220.143	4733.4	4721.8	545.03	0.42	3.81	4711.6	13.93	0.7053	40022.
8	224.989	225.133	4698.1	4687.6	545.30	0.42	3.83	4675.2	13.95	0.7030	40022.
9	229.979	230.124	4662.9	4652.6	545.52	0.42	3.83	4640.7	13.96	0.7007	39992.
10	234.970	235.156	4627.8	4617.3	545.81	0.42	3.83	4606.0	13.99	0.6995	39985.
11	239.961	240.146	4593.7	4582.4	546.06	0.43	3.96	4570.4	13.96	0.7052	40076.
12	244.992	245.137	4560.4	4547.6	546.20	0.43	3.95	4536.0	14.01	0.7023	39986.
13	249.983	250.127	4525.1	4513.6	546.49	0.44	3.97	4500.8	14.01	0.7071	40142.
14	254.973	255.159	4490.9	4480.0	546.74	0.33	3.35	4468.3	14.06	0.6076	37602.
15	259.964	260.150	4462.9	4452.4	546.77	0.23	2.07	4440.5	14.02	0.5072	35531.
16	264.996	265.140	4440.5	4429.2	546.70	0.15	2.36	4417.4	14.08	0.4090	33170.
17	269.986	270.131	4420.8	4410.0	546.77	0.08	1.83	4396.7	14.11	0.3076	30419.
18	274.977	275.121	4401.7	4391.2	546.79	0.08	1.73	4379.0	14.10	0.3070	30077.
19	279.968	280.153	4384.8	4375.2	546.82	0.07	1.72	4362.1	14.12	0.2856	29794.
20	284.958	285.144	4369.5	4358.9	546.83	0.04	1.40	4347.0	14.16	0.1983	28007.
21	289.990	290.134	4357.3	4347.2	546.84	0.00	0.88	4334.2	14.13	0.0294	25122.
22	294.981	295.125	4347.6	4337.5	546.79	0.0	0.40	4325.6	14.16	0.0	21855.
23	299.971	300.157	4340.3	4329.3	546.77	0.0	0.32	4315.9	14.19	0.0	22165.
24	304.962	305.147	4330.8	4319.7	546.77	0.0	0.45	4307.1	14.19	0.0	22770.
25	309.994	310.138	4320.9	4310.2	546.83	0.0	0.45	4298.8	14.20	0.0	22918.
26	314.984	315.129	4312.3	4302.3	546.84	0.0	0.45	4289.2	14.20	0.0	22978.
27	319.975	320.119	4305.4	4294.2	546.83	0.0	0.40	4280.8	14.21	0.0	22804.
28	324.965	325.151	4297.2	4286.2	546.87	0.0	0.56	4273.3	14.23	0.0	20752.
29	329.956	330.141	4291.4	4280.9	546.81	0.0	-0.15	4267.7	14.16	0.0	20036.
30	334.988	335.132	4285.5	4274.4	546.85	0.0	0.30	4262.0	14.23	0.0	20786.

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T U R B I N E P A R A M E T E R S

TIME SLICE NO	BEGIN TIME (SEC)	END TIME (SEC)	SPEED (RPM)	TURB INLET STAT PR (PSIA)	TURB INLET TOT PR (PSIA)	TURB MANIF PR (PSIA)	TURB 1ST NOZ D/S PR (PSIA)	TURB SEAL PR (PSIA)	TURB EXH STAT PR (PSIA)	TURB EXH TOT PR (PSIA)
1	189.972	190.158	11263.	39.54	43.48	44.15	30.93	121.95	23.40	18.25
2	194.963	195.148	30765.	123.05	134.05	126.68	93.75	378.97	60.35	50.67
3	199.995	200.139	40076.	211.75	220.11	210.88	162.80	601.81	101.78	80.35
4	204.985	205.130	39980.	212.75	222.24	213.21	158.57	617.38	98.96	80.52
5	209.976	210.120	39998.	211.75	221.74	212.54	158.74	623.01	98.96	81.05
6	214.966	215.152	40028.	212.15	221.94	213.08	159.15	623.40	99.23	80.42
7	219.998	220.143	40022.	210.75	222.58	212.88	158.74	623.01	98.96	81.05
8	224.989	225.133	40022.	210.75	222.75	213.04	159.08	623.17	98.96	81.69
9	229.979	230.124	39992.	213.75	220.06	212.88	158.74	623.01	98.80	81.02
10	234.970	235.156	39985.	211.35	220.33	212.54	158.74	622.74	98.83	81.22
11	239.961	240.146	40076.	212.15	221.27	213.74	160.64	625.26	99.23	81.62
12	244.992	245.137	39986.	209.75	220.23	212.54	158.74	623.01	98.63	81.35
13	249.983	250.127	40142.	213.75	222.24	219.21	161.45	626.15	98.96	81.69
14	254.973	255.159	37682.	183.87	193.63	186.28	139.65	556.63	86.36	72.72
15	259.964	260.150	35531.	159.59	171.76	164.55	122.19	499.93	76.54	64.75
16	264.996	265.140	33170.	131.72	148.94	141.21	106.28	444.01	65.79	56.45
17	269.986	270.131	30419.	108.71	124.96	118.22	87.15	382.05	55.01	47.64
18	274.977	275.121	30077.	105.04	121.94	113.22	85.63	377.58	53.52	46.81
19	279.968	280.153	29794.	107.04	118.75	111.22	83.33	370.23	52.52	46.15
20	284.958	285.144	28007.	91.30	105.34	97.88	73.44	335.12	47.22	40.70
21	289.990	290.134	25122.	76.36	86.21	79.05	58.89	285.50	36.93	33.20
22	294.981	295.125	21855.	56.02	68.10	60.55	46.36	232.67	28.81	25.56
23	299.971	300.157	22165.	52.88	65.89	58.29	45.01	239.33	27.58	24.89
24	304.962	305.147	22770.	63.82	71.52	65.09	47.99	245.43	30.89	26.75
25	309.994	310.138	22918.	64.02	71.96	65.55	48.56	250.23	30.88	26.72
26	314.984	315.129	22978.	63.02	72.29	65.55	48.90	249.40	31.13	27.05
27	319.975	320.119	22804.	65.35	70.11	62.39	47.72	247.91	29.47	26.22
28	324.965	325.151	20752.	61.95	71.79	64.55	48.53	211.11	30.76	27.28
29	329.956	330.141	20036.	30.74	43.34	33.75	26.46	217.34	16.30	16.66
30	334.988	335.132	20786.	50.68	66.25	58.22	44.33	213.30	27.31	25.56

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T U R B I N E P A R A M E T E R S (CONTINUED)

TIME SLICE NO	SPEED (RPM)	TURB IN TOT TEMP 1 (DEG R)	TURB IN TOT TEMP 2 (DEG R)	TURB EXH TOT TEMP (DEG R)	TURB 2ND STG. PRESS (PSIA)	BHP (CALIB) (HP)	BHP (DELTA T) (HP)	TORQUE (FT-LB)	AVAIL. ENERGY (BTU/LB)
1	11263.	533.03	533.03	192.04	0.0	0.0	0.0	0.0	405.82
2	30765.	562.86	562.86	376.31	0.0	94.0	343.3	16.05	474.14
3	40076.	566.12	566.12	424.98	0.0	236.5	514.4	30.98	492.18
4	39980.	566.27	566.27	430.67	0.0	231.8	483.2	30.44	495.79
5	39998.	566.30	566.30	433.69	0.0	229.1	471.5	30.08	487.92
6	40028.	566.26	566.26	435.90	0.0	230.6	461.8	30.25	495.73
7	40022.	566.23	566.23	437.52	0.0	228.0	454.4	29.91	489.47
8	40022.	566.06	566.06	438.72	0.0	227.6	448.1	29.86	490.52
9	39992.	566.01	566.01	439.52	0.0	226.2	443.7	29.70	488.77
10	39985.	565.72	565.72	440.06	0.0	225.6	440.0	29.62	488.00
11	40076.	565.61	565.61	440.46	0.0	227.8	441.8	29.84	487.65
12	39986.	565.57	565.57	440.93	0.0	226.2	438.2	29.70	486.99
13	40142.	565.48	565.48	441.18	0.0	229.1	440.0	29.96	489.06
14	37602.	565.18	565.18	440.34	0.0	184.6	379.6	25.77	479.38
15	35531.	565.04	555.04	438.76	0.0	146.8	320.5	21.69	477.43
16	33170.	565.01	565.01	436.26	0.0	111.5	263.5	17.65	474.93
17	30419.	564.93	564.93	432.43	0.0	77.7	203.8	13.41	472.03
18	30077.	564.90	564.90	430.64	0.0	76.5	206.1	13.36	469.04
19	29794.	564.84	564.84	429.42	0.0	70.2	193.4	12.36	463.75
20	28007.	564.71	564.71	425.70	0.0	46.3	137.8	8.68	465.94
21	25122.	564.60	564.60	418.23	0.0	6.3	21.5	1.31	467.17
22	21855.	564.56	564.56	408.66	0.0	0.0	0.0	0.0	477.85
23	22165.	564.13	564.13	407.08	0.0	0.0	0.0	0.0	474.63
24	22770.	564.52	564.52	406.93	0.0	0.0	0.0	0.0	479.26
25	22918.	564.33	564.33	406.90	0.0	0.0	0.0	0.0	482.20
26	22978.	564.30	564.30	406.87	0.0	0.0	0.0	0.0	478.92
27	22804.	564.16	564.16	406.27	0.0	0.0	0.0	0.0	479.01
28	20752.	565.23	565.23	397.42	0.0	0.0	0.0	0.0	473.09
29	20036.	562.50	562.50	394.14	0.0	0.0	0.0	0.0	465.84
30	20786.	564.82	564.82	390.84	0.0	0.0	0.0	0.0	466.36

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T U R B I N E   P A R A M E T E R S (CONTINUED)

TIME SLICE NO	SPEED RPM	FLOW (LB/SEC)	PR RATIO (T-T)	U/C (T-T)	EFF (T-T)	GAMMA	CP (BTU/LBM-R)	SPEED PARA-METER	FLOW PARA-METER	TORQUE PARA-METER
1	11263.	0.0	2.3822	0.0382	0.1639	1.3842	3.5560	61.69	0.0	0.0
2	30765.	0.36776	2.6458	0.0964	0.3811	1.3882	3.5363	163.99	2.5563	0.0485
3	40076.	0.72813	2.7369	0.1233	0.4663	1.3891	3.5378	213.00	2.9828	0.0551
4	39980.	0.71194	2.7599	0.1225	0.4641	1.3891	3.5375	212.46	2.9939	0.0555
5	39998.	0.71033	2.7090	0.1236	0.4672	1.3891	3.5374	212.55	2.9940	0.0550
6	40028.	0.70770	2.7596	0.1227	0.4646	1.3891	3.5374	212.72	2.9801	0.0553
7	40022.	0.70527	2.7192	0.1234	0.4669	1.3891	3.5375	212.70	2.9613	0.0545
8	40022.	0.70301	2.7268	0.1233	0.4665	1.3891	3.5376	212.73	2.9491	0.0543
9	39992.	0.70071	2.7161	0.1234	0.4668	1.3890	3.5376	212.58	2.9752	0.0547
10	39985.	0.69951	2.7127	0.1235	0.4671	1.3890	3.5378	212.59	2.9657	0.0545
11	40076.	0.70522	2.7110	0.1238	0.4680	1.3890	3.5379	213.10	2.9770	0.0547
12	39986.	0.70231	2.7070	0.1236	0.4675	1.3890	3.5379	212.63	2.9786	0.0547
13	40142.	0.70708	2.7207	0.1239	0.4681	1.3890	3.5380	213.48	2.9714	0.0547
14	37602.	0.60760	2.6627	0.1172	0.4479	1.3888	3.5371	200.02	2.9299	0.0540
15	35531.	0.50717	2.6527	0.1110	0.4285	1.3887	3.5363	189.03	2.7567	0.0512
16	33170.	0.40903	2.6388	0.1039	0.4057	1.3885	3.5354	176.47	2.5637	0.0481
17	30419.	0.30757	2.6228	0.0955	0.3782	1.3883	3.5345	161.85	2.2976	0.0435
18	30077.	0.30702	2.6048	0.0948	0.3756	1.3883	3.5344	160.03	2.3502	0.0444
19	29794.	0.28562	2.5733	0.0944	0.3744	1.3883	3.5343	158.54	2.2450	0.0422
20	28007.	0.19828	2.5879	0.0885	0.3543	1.3882	3.5339	149.04	1.7560	0.0334
21	25122.	0.02941	2.5971	0.0793	0.3218	1.3881	3.5332	133.70	0.3183	0.0061
22	21855.	0.0	2.6646	0.0682	0.2812	1.3879	3.5325	116.32	0.0	0.0
23	22165.	0.0	2.6467	0.0694	0.2857	1.3879	3.5327	118.01	0.0	0.0
24	22770.	0.0	2.6734	0.0710	0.2914	1.3880	3.5326	121.19	0.0	0.0
25	22918.	0.0	2.6930	0.0712	0.2923	1.3879	3.5328	122.00	0.0	0.0
26	22978.	0.0	2.6724	0.0716	0.2939	1.3879	3.5328	122.32	0.0	0.0
27	22804.	0.0	2.6738	0.0711	0.2919	1.3879	3.5328	121.41	0.0	0.0
28	20752.	0.0	2.6312	0.0651	0.2696	1.3880	3.5322	110.38	0.0	0.0
29	20036.	0.0	2.6022	0.0633	0.2630	1.3876	3.5329	106.84	0.0	0.0
30	20786.	0.0	2.5924	0.0657	0.2717	1.3879	3.5322	110.60	0.0	0.0

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HYBRID BEARING DATA
PUMP - END (PAGE 1)

TIME SLICE NO	PUMP BRG SUPPLY U/S PRESS (PSIA)	PUMP BRG SUPPLY TEMP (DEG R)	PUMP BRG SUPPLY D/S ORIF PRESS (PSIA)	PUMP BRG SUPPLY ORIF DP (PSID)	PUMP BRG SUPPLY MANIF PRESS (PSIA)	--- PUMP BRG PAD PRESSURES --- 3.00 OCLOCK (PSIA)	9.00 OCLOCK (PSIA)	6.30 OCLOCK (PSIA)
1	115.9	54.1	119.9	1.8	130.3	109.6	108.5	1.3
2	195.0	49.8	187.5	13.4	198.6	123.7	118.2	1.1
3	263.5	49.7	248.7	20.5	259.5	141.7	136.7	1.1
4	266.5	49.1	251.1	20.5	262.4	146.9	141.7	1.2
5	265.5	48.8	250.2	20.7	261.5	144.5	139.5	1.1
6	267.3	48.8	252.0	20.6	262.9	146.7	141.2	1.1
7	264.6	48.6	249.9	20.5	261.4	144.5	138.9	1.1
8	265.5	48.5	250.6	20.4	261.8	144.9	139.8	1.5
9	266.8	48.7	251.9	19.8	262.9	146.1	140.9	1.2
10	264.1	48.5	249.4	19.3	261.4	143.6	138.9	1.5
11	266.8	48.5	251.5	19.3	262.9	144.8	139.7	1.1
12	264.5	48.5	249.9	18.9	261.5	143.6	138.6	1.1
13	266.0	48.5	250.9	18.7	262.0	142.9	138.5	1.1
14	246.4	48.3	233.5	16.1	245.6	140.1	134.8	0.9
15	228.2	48.0	217.5	13.9	228.9	134.9	129.7	0.9
16	212.8	47.8	204.7	11.6	216.1	132.7	127.2	0.9
17	193.1	47.8	187.0	9.2	198.6	126.6	121.3	1.1
18	192.6	47.7	186.3	8.5	197.9	127.6	122.1	1.1
19	190.9	47.7	184.7	7.9	196.6	127.6	122.3	1.0
20	179.7	47.8	175.4	6.4	186.9	124.5	120.4	1.0
21	165.8	47.8	163.0	4.3	174.7	122.9	118.5	0.9
22	149.1	48.4	148.5	2.0	159.6	118.8	113.2	1.0
23	151.6	48.5	151.5	1.8	163.0	120.7	115.9	1.0
24	153.0	48.2	151.9	2.2	163.2	119.2	113.8	1.0
25	155.1	48.2	154.4	1.8	165.5	120.9	116.5	1.1
26	154.0	48.2	152.5	2.3	164.0	119.4	113.7	1.1
27	154.5	48.3	153.6	1.9	165.0	120.8	116.2	1.1
28	142.6	49.1	142.5	0.6	154.1	116.5	111.8	1.1
29	145.2	49.0	145.8	0.4	156.9	118.5	114.2	1.1
30	144.9	49.3	144.8	0.9	156.1	117.4	113.1	1.1

ORIGINAL PAGE IS
OF POOR QUALITY

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 12A
TEST DATE 7-09-82

PROCESSING DATE 7-13-82
TEST DURATION, SEC 202.00

HYBRID BEARING DATA
PUMP - END (PAGE 2)

TIME SLICE NO	PUMP BRG SUMP PRESSURE (PSIA)	PUMP BRG SUMP OUT PRESSURE (PSIA)	PUMP BRG SUMP OUT TEMP (DEG R)	SHAFT SPEED (RPM)	CARTRIDGE SPEED (RPM)	PUMP BRG FLOW (LB/SEC)	LH2 DENSITY AT ORIF (PCF)	AVERAGE PAD PRESSURE (PSIA)	PUMP BRG PRESSURE RATIO
1	105.2	58.1	45.7	11263.	416.	0.0119	0.6330	109.0	0.1518
2	104.7	58.1	46.3	30765.	21420.	0.0813	3.8925	120.9	0.1728
3	102.8	59.5	46.6	40076.	35714.	0.1018	3.9764	139.2	0.2324
4	103.7	58.8	46.5	39980.	39828.	0.1022	4.0117	144.3	0.2559
5	102.0	58.1	46.3	39998.	39797.	0.1029	4.0292	142.0	0.2505
6	103.7	58.3	46.2	40028.	39510.	0.1027	4.0329	144.0	0.2528
7	101.9	57.7	46.2	40022.	39379.	0.1026	4.0413	141.7	0.2495
8	102.6	57.7	46.2	40022.	39104.	0.1023	4.0433	142.4	0.2496
9	104.1	58.0	46.2	39992.	38803.	0.1009	4.0390	143.5	0.2479
10	102.0	57.6	46.2	39985.	38507.	0.0996	4.0430	141.2	0.2464
11	103.5	57.9	46.2	40076.	38035.	0.0997	4.0480	142.3	0.2434
12	102.7	57.5	46.1	39986.	37562.	0.0985	4.0472	141.1	0.2415
13	102.8	57.6	46.0	40142.	36841.	0.0981	4.0487	140.7	0.2382
14	104.3	57.3	46.0	37602.	36639.	0.0907	4.0382	137.5	0.2347
15	102.8	55.8	45.6	35531.	35313.	0.0844	4.0394	132.3	0.2340
16	104.6	55.7	45.3	33170.	33168.	0.0769	4.0319	129.9	0.2269
17	103.9	55.0	45.1	30419.	30426.	0.0685	4.0154	123.9	0.2122
18	105.0	55.0	45.0	30077.	30116.	0.0660	4.0169	124.9	0.2142
19	105.2	55.0	45.1	29794.	29771.	0.0635	4.0156	124.9	0.2158
20	104.9	54.6	45.0	28007.	28030.	0.0570	4.0024	122.4	0.2136
21	106.8	55.3	44.8	25122.	25146.	0.0465	3.9845	120.7	0.2036
22	105.6	53.5	44.2	21855.	21925.	0.0318	3.9264	116.0	0.1920
23	107.1	54.1	44.3	22165.	22153.	0.0300	3.9228	118.3	0.2002
24	105.1	53.7	44.4	22770.	22811.	0.0330	3.9438	116.5	0.1957
25	106.8	54.2	44.5	22918.	22953.	0.0298	3.9497	118.7	0.2029
26	105.0	53.7	44.5	22978.	23007.	0.0337	3.9461	116.5	0.1958
27	106.8	54.1	44.5	22804.	22769.	0.0306	3.9409	118.5	0.2013
28	105.1	53.5	44.3	20752.	19795.	0.0176	3.8766	114.1	0.1845
29	107.6	55.8	44.8	20036.	18752.	0.0148	3.8830	116.4	0.1770
30	107.0	54.2	44.7	20786.	17794.	0.0213	3.8646	115.3	0.1686

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 12A
TEST DATE 7-09-82

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H Y B R I D   B E A R I N G   D A T A
PUMP - END (PAGE 3)

TIME SLICE NO	BRG DELTA P ORIFICE PSID	BRG DELTA P FILM PSID	BRG DELTA P TOTAL PSID	ORIFICE RESISTANCE SEC**2/ LB-IN**2	FLUID FILM RESISTANCE SEC**2/ LB-IN**2	POISEUILLE RENOLDS NO	COUETTE RENOLDS NO	LAMBDA BRG NO	TORQUE FLUID FILM (TEMP) IN-LBS
1	21.3	3.8	25.1	150114.9	26868.8	13299211.	276.	0.00007	-411.3470
2	77.7	16.2	93.9	11743.3	2454.0	17585653.	22612.	0.01061	-4.6133
3	120.3	36.4	156.7	11609.7	3515.1	24456081.	35379.	0.01524	-3.2612
4	118.1	40.6	158.7	11314.5	3891.7	22343851.	38059.	0.01798	-2.6227
5	119.5	39.9	159.5	11296.0	3775.3	22011164.	37757.	0.01825	-2.5149
6	119.0	40.2	159.2	11274.4	3813.5	21964338.	37473.	0.01802	-2.5542
7	119.7	39.8	159.5	11365.1	3778.1	21802964.	37219.	0.01818	-2.4255
8	119.5	39.7	159.2	11420.8	3798.6	21792690.	36976.	0.01800	-2.4293
9	119.5	39.4	158.8	11742.5	3867.6	21967000.	36828.	0.01767	-2.4953
10	120.2	39.3	159.5	12107.8	3958.3	22013926.	36513.	0.01765	-2.3817
11	120.7	38.8	159.5	12142.0	3905.2	22066795.	36090.	0.01731	-2.3053
12	120.4	38.3	158.7	12414.2	3953.5	22100432.	35714.	0.01711	-2.4746
13	121.3	37.9	159.3	12614.4	3944.9	22401806.	35151.	0.01664	-2.5364
14	108.2	33.2	141.4	13137.5	4028.6	19813274.	34922.	0.01769	-2.2428
15	96.6	29.5	126.1	13576.2	4146.8	17671467.	33633.	0.01830	-2.1402
16	86.2	25.3	111.4	14560.9	4273.8	15937823.	31810.	0.01796	-2.1247
17	74.6	20.1	94.7	15904.0	4283.6	14023575.	29535.	0.01752	-2.1361
18	73.0	19.9	92.9	16749.1	4564.8	13756214.	29229.	0.01740	-2.0975
19	71.7	19.7	91.4	17783.0	4892.8	13580507.	28925.	0.01728	-2.0187
20	64.4	17.5	81.9	19810.6	5380.5	12458595.	27457.	0.01686	-1.9634
21	54.1	13.8	67.9	24976.9	6385.1	10678109.	24927.	0.01582	-1.8828
22	43.6	10.4	53.9	43026.9	10224.2	9172445.	22363.	0.01438	-1.9611
23	44.7	11.2	55.9	49697.2	12437.0	9542029.	22621.	0.01419	-1.8532
24	46.7	11.4	58.1	42817.8	[illegible]	9659730.	23076.	0.0148[illegible]	-1.8144
25	46.8	11.9	58.7	52541.1	13370.6	9693156.	23155.	0.01478	-1.5505
26	47.5	11.6	59.0	41774.7	10171.6	9787429.	23249.	0.01492	-1.7778
27	46.5	11.7	58.2	49473.7	12472.1	9706984.	23063.	0.01462	-1.6670
28	39.9	9.0	49.0	129138.2	29214.1	8875286.	20657.	0.01291	-1.3490
29	40.6	8.7	49.3	184262.8	39617.9	8945289.	19578.	0.01199	-1.0844
30	40.8	8.3	49.1	90339.7	18313.7	9158324.	18756.	0.01124	-1.7657

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LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 12A
TEST DATE 7-09-82

PROCESSING DATE 7-13-82
TEST DURATION, SEC 202.00

H Y B R I D B E A R I N G D A T A
PUMP AND TURBINE END (PAGE 4)

TIME SLICE NO	PUMP: HS BRG CLEARANCE RADIAL IN	PUMP: VISCOSITY PUMP BRG LB-HR/FT**2 * E10	PUMP: CSUBP PUMP BRG BTU/ LB-R	TURBINE: HS BRG CLEARANCE RADIAL IN	TURBINE: VISCOSITY TURB BRG LB-HR/FT**2 * E10	TURBINE: CSUBP TURB BRG BTU/ LB-R	TURBINE: POISEUILLE RENOLDS NO	TURBINE: COUETTE RENOLDS NO	TURBINE: LAMBDA TURB NO
1	0.00246	0.11043	5.6615	0.00246	0.11542	8.5465	7255508.	0.	0.0000
2	0.00238	0.46594	3.9495	0.00245	0.51342	3.1959	36779428.	2872.	0.0007
3	0.00226	0.47523	3.8115	0.00245	0.50731	3.1283	64898611.	5016.	0.0007
4	0.00222	0.48935	3.6595	0.00245	0.51686	3.0831	65232314.	4849.	0.0007
5	0.00222	0.49566	3.6018	0.00245	0.52411	3.0515	64595043.	4928.	0.0007
6	0.00223	0.49716	3.5862	0.00245	0.52451	3.0494	64718656.	5079.	0.0008
7	0.00223	0.50066	3.5568	0.00245	0.52508	3.0474	64458349.	4910.	0.0007
8	0.00223	0.50142	3.5496	0.00245	0.52691	3.0400	64109745.	4990.	0.0007
9	0.00223	0.49959	3.5646	0.00245	0.52708	3.0392	64'40231.	4857.	0.0007
10	0.00224	0.50147	3.5503	0.00245	0.52664	3.0401	64,47469.	4913.	0.0007
11	0.00224	0.50285	3.5375	0.00245	0.52874	3.0313	64333507.	5065.	0.0008
12	0.00225	0.50299	3.5375	0.00245	0.52824	3.0345	63861232.	4832.	0.0007
13	0.00225	0.50285	3.5390	0.00245	0.52983	3.0262	64471281.	4961.	0.0007
14	0.00226	0.50500	3.5239	0.00245	0.52092	3.0806	57327327.	4806.	0.0008
15	0.00227	0.51076	3.4807	0.00245	0.52834	3.0608	50536481.	4451.	0.0008
16	0.00229	0.51289	3.4653	0.00245	0.53146	3.0684	43222322.	4107.	0.0009
17	0.00231	0.51206	3.4770	0.00245	0.52835	3.1156	36405254.	3686.	0.0009
18	0.00232	0.51318	.4671	0.00245	0.53378	3.0916	35432428.	3815.	0.0009
19	0.00232	0.51336	3.4656	0.00245	0.53627	3.0829	34528860.	3786.	0.0010
20	0.00233	0.51183	3.4802	0.00245	0.53802	3.0973	29461488.	3650.	0.0010
21	0.00235	0.51009	3.4963	0.00245	0.53420	3.1461	23850077.	3229.	0.0010
22	0.00238	0.49441	3.6416	0.00246	0.50848	3.3286	19505651.	687.	0.0003
23	0.00238	0.49295	3.6527	0.00245	0.50015	3.3779	20950632.	4780.	0.0017
24	0.00237	0.49907	3.5973	0.00245	0.52791	3.1958	20313978.	5670.	0.0021
25	0.00237	0.50106	3.5767	0.00245	0.52633	3.2045	20575882.	5604.	0.0020
26	0.00237	0.49949	3.5935	0.00245	0.52484	3.2137	20594221.	5498.	0.0020
27	0.00237	0.49816	3.6035	0.00245	0.52402	3.2192	20532871.	5370.	0.0019
28	0.00239	0.48002	3.7936	0.00244	0.46430	3.6920	18619814.	7997.	0.0029
29	0.00240	0.48181	3.7706	0.00244	0.51247	3.3075	18143025.	9355.	0.0037
30	0.00240	0.47570	3.8411	0.00244	0.51131	3.3252	16505833.	9979.	0.0041

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 12A
TEST DATE 7-09-82

PROCESSING DATE 7-13-82
TEST DURATION, SEC 202.00

ORIGINAL PAGE IS OF POOR QUALITY

H Y B R I D B E A R I N G D A T A
TURBINE END (PAGE 1)

TIME SLICE NO	TURB BRG SUPPLY U/S PRESS (PSIA)	TURB BRG SUPPLY U/S TEMP (DEG R)	TURB BRG SUPPLY D/S ORIF PRESS (PSIA)	TURB BRG SUPPLY ORIF DP (PSID)	TURB BRG SUPPLY MANIF PRESS (PSIA)	TURB BRG DISCH PRESS (PSIA)	TURB BRG SUMP PRESS (PSIA)	-- TURBINE BRG -- DISCHARGE LINE PRESS (PSIA)	TEMP (DEG R)
1	130.8	55.4	126.4	22.3	131.5	134.3	114.3	50.7	45.4
2	486.3	51.9	467.6	46.3	443.4	310.4	285.4	88.7	50.6
3	777.6	55.8	745.5	62.6	703.4	448.4	420.8	124.6	54.3
4	800.2	55.5	768.4	60.1	719.6	457.5	430.5	125.9	54.4
5	805.5	55.1	773.3	59.7	724.7	459.9	432.3	126.2	54.5
6	807.7	55.1	775.3	59.7	726.3	460.8	432.8	127.4	54.6
7	805.0	55.1	773.1	59.4	724.4	459.5	431.8	127.4	54.6
8	807.0	55.0	774.1	58.9	725.4	460.2	432.8	126.9	54.5
9	806.5	55.0	774.5	59.0	725.6	460.8	432.8	127.4	54.6
10	804.0	54.9	772.2	58.4	724.1	459.2	430.3	127.6	54.6
11	808.8	54.9	777.3	58.7	728.3	461.7	433.1	127.9	54.6
12	805.4	54.9	772.9	58.3	724.2	459.8	431.8	127.2	54.5
13	809.9	54.8	778.0	58.6	729.7	462.0	433.0	128.0	54.6
14	719.9	54.2	691.1	53.7	648.5	419.9	392.8	117.5	53.7
15	647.8	52.9	622.6	49.4	586.1	384.1	357.0	107.6	52.6
16	575.6	51.9	552.4	45.7	522.6	350.0	325.7	99.3	51.9
17	493.9	51.2	474.1	41.4	449.8	309.3	286.0	90.5	50.9
18	488.2	50.8	468.4	40.9	443.9	308.0	282.0	89.8	50.7
19	478.5	50.6	457.8	40.4	436.2	303.3	277.4	88.3	50.5
20	432.0	50.0	413.4	37.8	394.7	281.4	258.7	81.3	49.8
21	364.8	49.5	349.3	33.4	335.8	250.3	227.3	73.8	48.8
22	292.6	49.8	279.1	29.9	272.3	213.8	191.0	68.6	48.1
23	302.5	50.4	288.7	30.3	281.1	219.2	195.2	71.1	48.5
24	311.5	49.1	298.3	30.7	290.6	223.3	199.7	69.8	48.3
25	317.0	49.2	303.0	30.9	293.8	226.0	202.1	70.5	48.4
26	316.8	49.3	303.0	31.1	292.9	224.9	201.6	70.3	48.3
27	314.1	49.3	300.7	31.0	291.5	224.6	200.8	70.3	48.3
28	261.5	51.6	249.7	28.2	245.7	199.7	177.0	69.2	48.2
29	275.0	49.4	263.7	28.7	258.5	203.0	180.2	66.3	47.8
30	266.3	49.3	255.1	28.3	249.9	202.2	178.8	65.9	47.8

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 12 A
TEST DATE 7-09-82

PROCESSING DATE 7-13-82
TEST DURATION, SEC 202.00

H Y B R I D B E A R I N G D A T A
TURBINE END (PAGE 2)

TIME SLICE NO	SHAFT SPEED (RPM)	TURBINE CARTRIDGE SPEED (RPM)	TURBINE H/S BRG FLOW (LB/SEC)	LH2 DENSITY AT ORIF (PCF)	TURB BRG SUPPLY MANIF PRESS (PSIA)	TURB BRG DISCH PRESS (PSIA)	TURB BRG SUMP PRESS (PSIA)	HYDROSTATIC BEARING DELTA PRESS (PSID)
1	11263.	1.	0.0644	0.740	131.5	134.3	114.3	17.22
2	30765.	2876.	0.2175	4.067	443.4	310.4	285.4	157.99
3	40076.	5080.	0.2543	4.114	700.4	448.4	420.8	279.56
4	39980.	4960.	0.2499	4.142	719.6	457.5	430.5	289.09
5	39998.	5077.	0.2498	4.160	724.7	459.9	432.3	292.39
6	40028.	5235.	0.2497	4.162	726.3	460.8	432.8	293.44
7	40022.	5062.	0.2491	4.163	724.4	459.5	431.8	292.55
8	40022.	5155.	0.2482	4.168	725.4	460.2	432.8	292.58
9	39992.	5017.	0.2484	4.168	725.6	460.8	432.8	292.75
10	39985.	5073.	0.2476	4.167	724.1	459.2	430.3	293.78
11	40076.	5242.	0.2480	4.172	728.3	461.7	433.1	295.23
12	39986.	4996.	0.2471	4.171	724.2	459.8	431.8	292.38
13	40142.	5140.	0.2478	4.175	729.7	462.0	433.0	296.70
14	37602.	4910.	0.2361	4.139	648.5	419.9	392.8	255.71
15	35531.	4559.	0.2268	4.146	586.1	384.1	357.0	229.08
16	33170.	4205.	0.2178	4.137	522.6	350.0	325.7	196.88
17	30419.	3750.	0.2066	4.100	449.8	309.3	286.0	163.73
18	30077.	3903.	0.2057	4.120	443.9	308.0	282.0	161.90
19	29794.	3882.	0.2045	4.123	436.2	303.3	277.4	158.86
20	28007.	3744.	0.1975	4.113	394.7	281.4	258.7	135.99
21	25122.	3287.	0.1851	4.085	335.8	250.3	227.3	108.45
22	21855.	676.	0.1733	4.001	272.3	213.8	191.0	81.39
23	22165.	4681.	0.1741	3.981	281.1	219.2	195.2	85.97
24	22770.	5725.	0.1768	4.057	290.6	223.3	199.7	90.89
25	22918.	5650.	0.1773	4.055	293.8	226.0	202.1	91.64
26	22978.	5534.	0.1778	4.052	292.9	224.9	201.6	91.29
27	22804.	5399.	0.1775	4.048	291.5	224.6	200.8	90.75
28	20752.	7546.	0.1653	3.860	245.7	199.7	177.0	68.73
29	20036.	9308.	0.1698	4.007	258.5	203.0	180.2	78.28
30	20786.	9919.	0.1686	4.001	249.9	202.2	178.8	71.11

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

PAGE 12. 1

RUN NUMBER 12 B
TEST DATE 7-09-82

PROCESSING DATE 7-13-82
TEST DURATION, SEC 202.00

COMMENTS . . .
TEST 12B

AMBIENT PRESSURE		13.8000
LO2 VENTURI (GG)		
P/N V160248-SGR	UPSTREAM DIAMETER	0.0
S/N 8871	THROAT DIAMETER	0.0
	THROAT CD	0.0
GH2 VENTURI (TURB)		
P/N VP031200-SGR	UPSTREAM DIAMETER	2.3000
S/N 9731	THROAT DIAMETER	1.3085
	THROAT CD	0.9873
LH2 VENTURI (GG)		
P/N V320471-SGR	UPSTREAM DIAMETER	0.0
S/N 8873	THROAT DIAMETER	0.0
	THROAT CD	0.0
LH2 VENTURI (PUMP DISCH)		
P/N V320709-SGR	UPSTREAM DIAMETER	1.6890
S/N 8874	THROAT DIAMETER	0.7090
	THROAT CD	0.9760
	TURBINE SYSTEM EFF. AREA	0.70470
	TURBINE EXHAUST ORIFICE 4 EACH	0.31200
	4 EACH	0.32500
	1 EACH	0.30800
	4 EACH	0.37500
	4 EACH	0.31250
	TURBINE EXHAUST EFF. AREA	1.28100

HYDROSTATIC BEARING SUPPLY SYSTEM
TURBINE INLET DUCT DIA 0.334 ORIFICE DIA 0.194
PUMP INLET DUCT DIA 0.402 ORIFICE DIA 0.175

ORIGINAL PAGE IS
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MK48-F PAGE 12. 2
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 12 B PROCESSING DATE 7-13-82
TEST DATE 7-09-82 TEST DURATION, SEC 202.00

G A S E O U S H Y D R O G E N T U R B I N E D R I V E P A R A M E T E R S

TIME SLICE NO	BEGIN TIME (SEC)	END TIME (SEC)	REG U/S PR (PSIA)	VENTURI U/S PR (PSIA)	VENTURI U/S TEMP (DEG R)	VENTURI DELTA PR (PSID)	SPIN VALVE POSN	SPIN VALVE U/S PR (PSIA)	FAC DUCT PR (PSIA)	TURB GH2 FLOW (LB/SEC)	SPEED (RPM)
1	339.978	340.123	4279.3	4268.6	546.84	0.0	-0.09	4256.3	14.23	0.0	16948.
2	344.969	345.154	4274.0	4263.4	546.85	0.0	0.29	4251.2	14.23	0.0	20695.
3	349.959	350.145	4269.7	4258.0	546.85	0.0	-0.26	4246.5	14.22	0.0	17038.
4	354.991	355.136	4264.4	4254.3	545.87	0.0	-0.21	4242.3	14.23	0.0	19387.
5	359.982	360.126	4257.7	4247.3	545.93	0.0	0.43	4234.3	14.21	0.0	20300.
6	364.972	365.117	4253.6	4242.2	547.02	0.0	0.10	4229.4	14.23	0.0	17921.
7	369.963	370.149	4247.4	4236.1	547.08	0.0	-0.10	4223.7	14.23	0.0	20214.
8	374.954	375.139	4242.3	4230.4	547.10	0.0	0.27	4218.5	14.23	0.0	18811.
9	375.985	376.129	4240.0	4228.9	547.13	0.0	0.03	4216.2	14.23	0.0	17939.
10	376.480	376.624	4239.0	4228.6	547.14	0.0	0.26	4215.6	14.21	0.0	21146.
11	376.975	377.119	4238.0	4227.7	547.11	0.0	0.55	4213.9	14.23	0.0	19843.
12	377.469	377.614	4237.0	4226.6	547.14	0.25	3.01	4212.4	14.23	0.5249	32389.
13	377.964	378.109	4233.0	4222.2	547.23	0.68	5.09	4207.2	14.23	0.8542	40827.
14	378.459	378.604	4228.2	4215.5	547.56	1.70	8.24	4198.5	14.23	1.3507	50207.
15	378.996	379.099	4219.4	4207.3	547.93	3.61	12.25	4183.6	15.36	1.9656	59558.
16	379.490	379.635	4207.6	4192.7	548.28	6.88	17.20	4161.5	21.80	2.7073	68987.
17	379.985	380.130	4192.8	4174.7	548.70	11.16	22.14	4133.1	29.46	3.4382	77437.
18	380.480	380.625	4175.9	4156.5	549.06	13.82	24.83	4108.1	33.65	3.8173	81701.
19	380.975	381.120	4158.2	4136.5	549.42	15.76	26.66	4083.5	36.34	4.0654	84242.
20	381.470	381.615	4139.6	4118.2	549.65	17.14	27.95	4061.0	38.29	4.2309	85815.
21	381.965	382.109	4120.3	4097.6	549.60	18.19	28.91	4038.5	39.50	4.3492	86800.
22	382.460	382.604	4100.9	4077.8	549.42	18.91	29.59	4016.8	40.30	4.4258	87479.
23	382.996	383.099	4080.5	4057.4	549.17	19.51	30.22	3994.0	40.99	4.4865	87929.
24	383.491	383.594	4061.0	4037.0	548.91	19.93	30.67	3973.3	41.50	4.5324	88249.
25	383.986	384.130	4040.5	4016.2	548.58	20.38	31.02	3952.0	41.81	4.5675	88380.
26	384.481	384.625	4020.4	3996.0	548.19	20.65	31.34	3931.0	42.11	4.5898	88662.
27	384.976	385.120	4023.8	4012.6	548.35	0.0	-1.11	3988.7	14.23	0.0	38082.
28	385.471	385.615	4010.9	3999.7	548.14	0.0	-1.11	2144.0	14.23	0.0	[illegible]

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 12B
TEST DATE 7-09-82

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H Y B R I D   B E A R I N G   D A T A
PUMP - END (PAGE 1)

TIME SLICE NO	PUMP BRG SUPPLY U/S PRESS (PSIA)	PUMP BRG SUPPLY TEMP (DEG R)	PUMP BRG SUPPLY D/S ORIF PRESS (PSIA)	PUMP BRG SUPPLY DIFF DP (PSID)	PUMP BRG SUPPLY MANIF PRESS (PSIA)	--- PUMP BRG PAD PRESSURES --- 3.00 OCLOCK (PSIA)	9.00 OCLOCK (PSIA)	6.30 OCLOCK (PSIA)
1	131.9	51.0	135.0	0.0	146.5	116.9	112.4	1.0
2	143.1	49.1	143.3	0.8	154.7	116.4	112.2	0.9
3	133.3	50.2	136.0	0.0	147.5	117.3	112.8	0.9
4	143.7	48.7	144.7	0.5	156.0	117.9	114.3	1.0
5	141.7	49.4	142.2	0.7	153.2	116.8	112.3	1.2
6	132.5	50.4	134.9	0.0	146.1	114.9	111.1	1.1
7	145.2	48.8	146.1	0.7	157.2	118.9	114.7	1.0
8	135.2	49.5	136.7	0.0	147.6	115.1	111.1	1.1
9	133.2	49.9	135.0	0.0	146.3	115.1	110.7	1.1
10	146.7	48.4	146.9	1.4	158.1	118.2	113.7	1.1
11	140.0	49.9	141.2	0.4	152.1	116.9	112.2	1.1
12	206.3	47.8	196.9	10.3	208.3	124.7	120.2	1.1
13	266.8	48.2	250.6	17.1	262.0	133.0	129.3	1.1
14	361.3	49.5	335.8	25.5	347.9	151.1	154.7	1.0
15	467.8	51.7	428.7	39.2	440.8	162.7	168.0	1.1
16	607.3	54.6	558.8	46.8	571.3	226.8	241.5	1.0
17	757.7	57.9	704.7	48.8	717.3	347.0	369.1	0.9
18	848.7	60.4	797.3	46.3	810.9	458.5	484.4	0.9
19	904.7	61.6	855.4	44.7	869.3	517.7	546.9	1.0
20	940.6	62.6	892.7	47.6	906.5	555.8	586.6	1.0
21	965.4	63.3	918.7	41.1	933.1	586.4	615.5	0.9
22	977.7	63.9	931.1	47.0	945.0	593.3	624.6	0.7
23	985.1	64.7	937.7	42.7	952.1	596.2	613.1	0.9
24	977.7	64.3	918.8	53.8	932.0	488.7	511.9	1.0
25	965.7	64.8	900.5	62.6	912.4	407.7	405.4	1.3
26	961.5	64.8	891.3	68.3	903.6	319.7	317.0	2.0
27	182.6	106.7	185.1	2.0	196.1	100.2	95.7	4.2
28	93.9	53.2	102.2	0.0	112.1	90.8	86.7	5.3
29	91.4	52.4	98.9	0.0	109.0	99.0	96.3	5.3

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OF POOR QUALITY

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 128
TEST DATE 7-09-82

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TEST DURATION, SEC 202.00

ORIGINAL PAGE IS
OF POOR QUALITY

H Y B R I D B E A R I N G D A T A
PUMP - END (PAGE 2)

TIME SLICE NO	PUMP BRG SUMP PRESSURE (PSIA)	PUMP BRG SUMP OUT PRESSURE (PSIA)	PUMP BRG SUMP OUT TEMP (DEG R)	SHAFT SPEED (RPM)	CARTRIDGE SPEED (RPM)	PUMP BRG FLOW (LB/SEC)	LH2 DENSITY AT ORIF (PCF)	AVERAGE PAD PRESSURE (PSIA)	PUMP BRG PRESSURE RATIO
1	107.7	56.3	44.6	16948.	15887.	0.0	3.7153	114.6	0.1786
2	105.8	54.1	44.8	20695.	17927.	0.0196	3.8748	114.3	0.1726
3	108.0	55.0	44.4	17038.	17177.	0.0	3.7834	115.1	0.1784
4	108.3	56.3	44.9	19387.	17288.	0.0158	3.[illegible]055	116.1	0.1637
5	106.6	53.4	44.4	20330.	17601.	0.0181	3.8494	114.6	0.1704
6	105.4	53.4	44.2	17921.	17890.	0.0	3.7633	113.0	0.1871
7	107.6	55.1	44.6	20214.	19516.	0.0192	3.8981	116.8	0.1860
8	105.2	52.9	44.1	18811.	18395.	0.0	3.8372	113.1	0.1863
9	105.5	52.9	43.9	17939.	17960.	0.0	3.8006	112.9	0.1823
10	107.0	54.7	44.6	21146.	19246.	0.0264	3.9257	115.9	0.1753
11	105.9	53.4	44.1	19863.	19246.	0.0144	3.8172	114.5	0.1867
12	106.0	57.0	45.7	3238[illegible].	20569.	0.0724	4.0254	122.4	0.1610
13	102.9	57.7	46.1	40827.	22326.	0.0940	4.0611	131.1	0.1776
14	102.1	62.5	47.0	50202.	23474.	0.1148	4.0788	152.9	0.2067
15	102.3	63.8	47.3	59558.	26371.	0.1472	4.0642	165.3	0.1862
16	99.3	65.1	47.4	68987.	49226.	0.154[illegible]	4.0394	234.2	0.2858
17	98.9	69.5	48.0	77437.	68108.	0.1577	4.0115	358.0	0.4191
18	100.1	75.6	48.9	81701.	76148.	0.1528	3.9713	471.4	0.5224
19	98.3	78.7	49.3	84242.	84308.	0.1500	3.9652	532.3	0.5630
20	98.2	81.3	49.6	85815.	85866.	0.1462	3.9499	571.2	0.5652
21	98.5	83.1	49.8	86830.	85809	0.1434	3.9380	600.9	0.6020
22	97.9	84.4	49.9	87479.	874[illegible].	0.1446	3.9232	608.9	0.6033
23	101.9	86.8	50.2	87929.	788[illegible]0.	0.1454	3.8953	604.6	0.5913
24	106.0	88.1	50.4	88249.	67[illegible]0.	0.1629	3.8829	500.3	0.4774
25	106.7	88.3	50.5	88380.	47921.	0.1755	3.8735	406.5	0.3722
26	104.4	88.9	50.6	88662.	18620.	0.1833	3.8721	318.3	0.2677
27	69.3	94.3	51.8	38082.	4183.	0.0093	0.3412	98.0	0.2264
28	86.3	83.0	50.3	12.	1844.	0.0	0.4620	88.7	0.0963
29	96.8	66.7	47.8	6.	461.	0.0	0.4592	97.7	0.0687

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LIQUID HYDROGEN TURBOPUMP ASSEMBLY

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H Y B R I D   B E A R I N G   D A T A
PUMP - END (PAGE 3)

TIME SLICE NO	BRG DELTA P ORIFICE PSID	BRG DELTA P FILM PSID	BRG DELTA P TOTAL PSID	ORIFICE RESISTANCE SEC**2/ LB-IN**2	FLUID FILM RESISTANCE SEC**2/ LB-IN**2	POISEUILLE RENOLDS NO	COUETTE RENOLDS NO	LAMBDA BRG NO	TORQUE FLUID FILM (TEMP) IN-LBS
1	31.8	6.9	38.8	************	************	8246265.	18643.	0.01044	0.0
2	40.4	8.4	48.9	105184.4	21943.5	8994220.	18808.	0.01152	-1.5386
3	32.4	7.0	39.5	************	************	7886464.	18557.	0.01099	0.0
4	39.9	7.8	47.7	160130.5	31333.3	8534308.	17944.	0.01123	-1.1119
5	38.7	7.9	46.6	118672.7	24387.6	8805019.	18642.	0.01123	-1.6624
6	33.1	7.6	40.7	************	************	8262851.	19430.	0.01144	0.0
7	40.3	9.2	49.6	109422.1	24996.6	8800326.	20215.	0.01264	-1.3385
8	34.[illegible]	7.9	42.4	************	************	8004664.	19481.	0.01219	0.0
9	33.4	7.4	40.8	************	************	7991574.	19269.	0.01173	0.0
10	42.2	9.0	51.1	60665.8	12899.6	8856772.	19751.	0.01258	-1.6845
11	37.6	8.6	46.2	180347.8	41400.5	8896269.	20524.	0.01223	-1.3961
12	85.9	16.5	102.3	16365.3	3141.4	16715196.	20642.	0.01059	-2.8341
13	130.9	28.3	159.2	14815.2	3198.7	26085530.	22428.	0.00911	-3.6816
14	195.0	50.8	245.8	14784.6	3853.1	42364946.	23982.	0.00698	-5.2955
15	275.5	63.0	338.5	13630.6	3118.8	64622306.	27875.	0.00578	-9.3744
16	337.1	134.9	472.0	14054.5	5622.9	51377362.	50574.	0.00896	-8.5295
17	359.3	259.2	618.5	14447.9	10421.6	56794985.	53444.	0.01415	-8.4913
18	339.4	371.3	710.8	14537.7	15904.0	48152100.	52669.	0.01673	-8.5037
19	337.0	434.0	771.0	14968.2	19280.1	36317306.	51069.	0.02176	-8.0144
20	335.3	473.0	808.3	15690.0	22133.9	35143215.	50131.	0.02219	-8.0468
21	332.2	502.4	834.6	16148.3	24424.8	34490932.	49511.	0.02240	-8.1117
22	336.1	511.1	847.2	16081.1	24453.4	33970351.	48892.	0.02251	-8.3413
23	347.5	502.7	850.2	16437.7	23781.2	49829979.	49153.	0.01537	-9.5512
24	431.7	394.4	826.1	16277.9	14870.0	73549332.	44761.	0.00941	-12.4584
25	505.8	299.8	805.6	16425.9	9736.6	96491806.	28279.	0.00451	-18.6660
26	585.3	214.0	799.2	17416.0	6367.3	125304666.	9306.	0.00115	-49.5513
27	98.1	28.7	126.8	1130123.1	330817.8	7814590.	590.	0.00072	-31.1736
28	23.4	2.5	25.9	************	************	11928566.	997.	0.00034	0.0
29	11.4	0.8	12.2	************	************	6829811.	304.	0.00009	0.0

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RUN NUMBER 12 B
TEST DATE 7-09-82

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H Y B R I D B E A R I N G D A T A
PUMP AND TURBINE END (PAGE 4)

TIME SLICE NO	PUMP: HS BRG CLEARANCE RADIAL IN	PUMP: VISCOSITY PUMP BRG LB-HR/FT**2 * E10	PUMP: CSUBP PUMP BRG BTU/ LB-R	TURBINE: HS BRG CLEARANCE RADIAL IN	TURBINE: VISCOSITY TURB BRG LB-HR/FT**2 * E10	TURBINE: CSUBP TURB BRG BTU/ LB-R	TURBINE: POISEUILLE RENOLDS NO	TURBINE: COUETTE RENOLDS NO	TURBINE: LAMBDA TURB NO
1	0.00241	0.43840	4.3753	0.00243	0.38302	4.3501	20912749.	12968.	0.0040
2	0.00240	0.47930	3.8016	0.00243	0.51328	3.3319	16536649.	11442.	0.0047
3	0.00240	0.45640	4.0887	0.00243	0.46650	3.7077	15897503.	11758.	0.0049
4	0.00240	0.48364	3.6883	0.00246	0.51824	3.2777	16985649.	1184.	0.0005
5	0.00240	0.47208	3.8851	0.00245	0.50145	3.4033	15968301.	5200.	0.0021
6	0.00240	0.45033	4.1832	0.00244	0.44841	3.8835	17127995.	9556.	0.0037
7	0.00239	0.48687	3.7159	0.00244	0.51666	3.2816	17644519.	9669.	0.0039
8	0.00240	0.47057	3.9058	0.00244	0.48281	3.5569	15675830.	10260.	0.0043
9	0.00240	0.46053	4.0361	0.00244	0.46202	3.7442	16535751.	10372.	0.0042
10	0.00239	0.49517	3.6345	0.00244	0.52357	3.2379	17202219.	9734.	0.0040
11	0.00239	0.46304	3.9990	0.00244	0.47558	3.5963	17927086.	10062.	0.0038
12	0.00239	0.51021	3.4937	0.00244	0.55631	2.9733	36502612.	7806.	0.0019
13	0.00237	0.50425	3.5361	0.00245	0.54959	2.9490	60978571.	4087.	0.0006
14	0.00237	0.48458	3.6976	0.00246	0.54306	2.9252	95590200.	360.	0.0000
15	0.00235	0.44472	4.1493	0.00244	0.53237	2.9319	133297055.	6919.	0.0005
16	0.00211	0.38696	4.4771	0.00244	0.52333	2.9302	182259187.	7737.	0.0004
17	0.00182	0.41101	4.3719	0.00246	0.51495	2.9426	237700142.	753.	0.0000
18	0.00166	0.41218	4.1968	0.00245	0.50504	2.9719	267910763.	3993.	0.0002
19	0.00149	0.41787	4.0895	0.00244	0.50538	2.9813	277637183.	8376.	0.0003
20	0.00146	0.41640	4.0664	0.00242	0.50584	2.9890	282341233.	12137.	0.0004
21	0.00144	0.41557	4.0439	0.00240	0.50496	2.9947	283378180.	15028.	0.0005
22	0.00142	0.41132	4.0845	0.00238	0.50335	2.9999	282813686.	17769.	0.0007
23	0.00161	0.40142	4.2038	0.00235	0.50332	3.0103	276756415.	21485.	0.0008
24	0.00183	0.36527	4.8581	0.00232	0.50351	3.0114	268408610.	24293.	0.0009
25	0.00213	0.32512	6.0971	0.00229	0.49986	3.0136	261327110.	26502.	0.0011
26	0.00240	0.26720	10.3183	0.00227	0.50279	3.0058	257126745.	27940.	0.0011
27	0.00245	0.16993	2.7020	0.00230	0.19280	4.8865	71292066.	15625.	0.0023
28	0.00245	0.10309	4.3452	0.00246	0.14387	2.9461	4094687.	138.	0.0002
29	0.00246	0.10378	5.4421	0.00246	0.13230	2.8374	484443.	1.	0.0000

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 128
TEST DATE 7-09-82

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TEST DURATION, SEC 202.00

H Y B R I D   B E A R I N G   D A T A
TURBINE END (PAGE 1)

TIME SLICE NO	TURB BRG SUPPLY U/S PRESS (PSIA)	TURB BRG SUPPLY U/S TEMP (DEG R)	TURB BRG SUPPLY D/S ORIF PRESS (PSIA)	TURB BRG SUPPLY ORIF DP (PSID)	TURB BRG SUPPLY MANIF PRESS (PSIA)	TURB BRG DISCH PRESS (PSIA)	TURB BRG SUMP PRESS (PSIA)	-- TURBINE BRG -- DISCHARGE PRESS (PSIA)	LINE TEMP (DEG R)
1	221.2	53.5	212.0	25.4	210.1	175.5	153.1	62.3	47.3
2	264.4	49.4	252.9	28.5	248.4	199.8	176.9	65.8	47.8
3	224.4	51.0	215.3	25.4	214.3	177.2	154.6	62.4	47.3
4	262.5	48.9	251.7	28.0	247.7	196.7	174.8	64.7	47.6
5	251.9	49.7	241.2	28.0	237.7	194.8	172.1	66.5	47.8
6	229.0	51.9	219.4	26.7	217.2	180.4	156.9	65.1	47.6
7	274.7	49.2	263.9	28.9	258.4	204.0	181.1	66.5	47.8
8	235.8	50.3	225.7	27.3	223.5	184.7	161.8	64.8	47.6
9	230.7	51.3	220.9	26.9	218.9	180.5	157.9	64.4	47.5
10	278.3	48.9	266.5	29.7	260.7	207.4	183.8	65.6	47.7
11	257.8	51.0	246.5	28.5	241.8	196.3	172.8	64.8	47.5
12	541.2	50.2	518.9	45.5	490.7	337.1	310.2	88.0	50.4
13	826.8	53.9	793.9	62.3	743.2	475.5	447.2	120.6	53.8
14	1222.5	58.9	1174.2	90.3	1094.0	668.6	639.4	159.8	57.0
15	1710.1	65.7	1639.0	121.7	1523.0	905.5	876.6	214.8	60.5
16	2298.8	73.9	2209.2	148.4	2052.4	1196.1	1169.3	281.1	65.6
17	2927.6	83.3	2814.9	182.7	2615.5	1512.5	1487.8	347.6	73.8
18	3277.7	89.9	3152.9	202.4	2930.9	1688.1	1663.9	400.1	81.3
19	3500.3	93.7	3369.1	213.3	3133.4	1800.5	1776.2	436.7	86.5
20	3646.4	96.3	3509.9	212.6	3265.7	1877.0	1847.9	459.9	90.0
21	3741.2	98.0	3601.1	210.8	3351.2	1919.6	1895.5	478.7	92.4
22	3803.9	99.3	3662.1	208.0	3409.9	1948.9	1923.8	490.0	94.2
23	3841.8	100.6	3700.8	203.7	3442.4	1967.0	1940.4	498.1	95.8
24	3880.1	101.2	3730.7	210.1	3479.5	1985.8	1957.1	504.6	96.8
25	3887.2	101.6	3745.4	201.8	3496.1	1990.3	1962.5	507.6	97.5
26	3922.8	101.5	3782.7	199.8	3531.8	2001.8	1972.9	509.7	97.8
27	625.8	89.3	606.0	35.6	583.6	342.3	319.2	151.7	64.0
28	128.4	81.8	124.0	14.5	128.9	120.6	102.0	86.5	50.9
29	86.9	76.7	83.6	14.8	93.3	105.6	86.2	67.6	51.0

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 128
TEST DATE 7-09-82

PROCESSING DATE 7-13-82
TEST DURATION, SEC 207.00

HYBRID BEARING DATA
TURBINE END (PAGE 2)

TIME SLICE NO	SHAFT SPEED (RPM)	TURBINE CARTRIDGE SPEED (RPM)	TURBINE H/S BRG FLOW (LB/SEC)	LH2 DENSITY AT ORIF (PCF)	TURB BRG SUPPLY MANIF PRESS (PSIA)	TURB BRG DISCH PRESS (PSIA)	TURB BRG SUMP PRESS (PSIA)	HYDROSTATIC BEARING DELTA PRESS (PSID)
1	16948.	10863.	0.1528	3.667	210.1	175.5	153.1	57.03
2	20695.	11384.	0.1690	3.998	248.4	199.8	176.9	71.47
3	17038.	11136.	0.1569	3.855	214.3	177.2	154.6	59.75
4	19387.	1175.	0.1681	4.019	247.7	196.7	174.8	72.89
5	20300.	5083.	0.1668	3.968	237.7	194.8	172.1	65.62
6	17921.	8865.	0.1596	3.799	217.2	180.4	156.9	60.22
7	20214.	9669.	0.1707	4.018	258.4	204.0	181.1	77.21
8	18811.	9874.	0.1635	3.909	223.5	184.7	161.8	61.73
9	17939.	9764.	0.1612	3.844	218.9	180.5	157.9	60.94
10	21146.	9809.	0.1733	4.038	260.7	207.4	183.8	76.91
11	19843.	9624.	0.1668	3.896	241.8	196.3	172.8	69.06
12	32389.	8223.	0.2186	4.186	490.7	337.1	310.2	180.51
13	40827.	4312.	0.2570	4.224	743.2	475.5	447.2	296.06
14	50202.	381.	0.3110	4.268	1094.0	668.6	639.4	454.62
15	59558.	7482.	0.3620	4.292	1523.0	905.5	876.6	646.48
16	68987.	8482.	0.4011	4.318	2052.4	1196.1	1169.3	883.07
17	77437.	832.	0.4455	4.328	2615.5	1512.5	1487.8	1127.74
18	81701.	4464.	0.4675	4.303	2930.9	1688.1	1663.9	1267.00
19	84242.	9549.	0.4798	4.299	3133.4	1800.5	1776.2	1357.18
20	85815.	14027.	0.4787	4.295	3265.7	1872.0	1847.9	1417.79
21	86800.	17549.	0.4765	4.292	3351.2	1919.6	1895.5	1455.79
22	87479.	20949.	0.4731	4.287	3409.9	1948.9	1923.8	1486.05
23	87929.	25733.	0.4673	4.272	3449.4	1957.0	1940.4	1508.97
24	88249.	29505.	0.4747	4.274	3479.5	1985.8	1957.1	1522.46
25	88380.	32582.	0.4650	4.268	3496.1	1990.3	1962.5	1533.58
26	88662.	34682.	0.4634	4.282	3531.8	2031.8	1972.9	1558.89
27	38082.	31396.	0.1282	1.840	580.6	342.3	319.2	761.33
28	12.	769.	0.0345	0.327	128.9	120.6	102.0	76.82
29	6.	4.	0.0293	0.231	90.3	105.6	86.9	3.44

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 14A
TEST DATE 7-15-82

PROCESSING DATE 7-21-82
TEST DURATION, SEC 148.00

COMMENTS . . .
TEST 14A

AMBIENT PRESSURE		13.8000
LO2 VENTURI (GG) P/N V160248-SGR S/N 8871	UPSTREAM DIAMETER	0.0
	THROAT DIAMETER	0.0
	THROAT CD	0.0
GH2 VENTURI (TURB) P/N VP031200-SGR S/N 9731	UPSTREAM DIAMETER	2.3000
	THROAT DIAMETER	1.3085
	THROAT CD	0.9873
LH2 VENTURI (GG) P/N V320471-SGR S/N 8873	UPSTREAM DIAMETER	0.0
	THROAT DIAMETER	0.0
	THROAT CD	0.0
LH2 VENTURI (PUMP DISCH) P/N V320709-SGR S/N 8874	UPSTREAM DIAMETER	1.6890
	THROAT DIAMETER	0.7090
	THROAT CD	0.9760
	TURBINE SYSTEM EFF. AREA	0.70470
	TURBINE EXHAUST ORIFICE 4 EACH	0.31200
	4 EACH	0.32500
	1 EACH	0.30800
	4 EACH	0.37500
	4 EACH	0.31250
	TURBINE EXHAUST EFF. AREA	1.28100

HYDROSTATIC BEARING SUPPLY SYSTEM
TURBINE INLET DUCT DIA 0.334 ORIFICE DIA 0.194
PUMP INLET DUCT DIA 0.402 ORIFICE DIA 0.175

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

PAGE 14. 2

RUN NUMBER 14A
TEST DATE 7-15-82

PROCESSING DATE 7-21-82
TEST DURATION, SEC 148.00

G A S E O U S   H Y D R O G E N   T U R B I N E   D R I V E   P A R A M E T E R S

TIME SLICE NU	BEGIN TIME (SEC)	END TIME (SEC)	REG U/S PR (PSIA)	VENTURI U/S PR (PSIA)	VENTURI U/S TEMP (DEG R)	VENTURI DELTA PR (PSID)	SPIN VALVE POSN	SPIN VALVE J/S PR (PSIA)	FAC DUCT PR (PSIA)	TURB GH2 FLOW (LB/SEC)	SPEED (RPM)
1	197.973	198.159	4965.5	4951.8	545.52	0.0	-1.24	4945.5	13.87	0.0	1048.
2	200.984	201.128	4962.5	4949.5	541.56	0.0	-0.58	4944.0	13.87	0.0	16852.
3	203.995	204.139	4956.2	4942.4	541.23	0.0	0.56	4936.8	13.88	0.0	24680.
4	206.964	207.150	4945.9	4932.4	542.59	0.07	1.40	4925.6	13.88	0.2870	29745.
5	209.975	210.161	4933.6	4920.9	543.29	0.07	1.40	4913.6	13.88	0.2895	29783.
6	212.986	213.130	4921.0	4908.1	543.95	0.07	1.40	4901.2	13.88	0.2890	29783.
7	215.997	216.141	4908.9	4896.0	544.31	0.07	1.40	4889.0	13.87	0.2886	29879.
8	218.966	219.152	4898.5	4883.8	544.72	0.07	1.40	4877.4	13.91	0.2882	29783.
9	221.977	222.122	4884.9	4872.6	544.99	0.07	1.40	4865.0	13.87	0.2879	29783.
10	224.988	225.133	4873.7	4860.1	545.40	0.07	1.41	4854.2	13.90	0.2873	29855.
11	227.999	228.143	4861.2	4847.5	545.60	0.07	1.40	4841.5	13.87	0.2871	29783.
12	230.969	231.154	4850.1	4836.3	546.12	0.07	1.41	4829.5	13.91	0.2867	29802.
13	233.979	234.124	4838.0	4824.3	546.36	0.07	1.43	4817.4	13.90	0.2864	29801.
14	236.990	237.135	4825.5	4813.7	546.66	0.07	1.43	4806.7	13.90	0.2860	29783.
15	239.960	240.145	4814.7	4800.2	546.82	0.08	1.61	4793.5	13.91	0.3055	30288.
16	242.971	243.156	4802.3	4787.9	547.06	0.09	1.61	4782.6	13.91	0.3051	30701.
17	245.982	246.126	4790.1	4777.8	547.12	0.04	1.27	4770.5	13.90	0.2181	28534.
18	248.992	249.137	4780.1	4766.5	547.20	0.04	1.15	4760.8	13.92	0.2179	28096.
19	251.962	252.148	4769.7	4757.0	547.26	0.04	1.08	4749.9	13.92	0.2139	27862.
20	254.973	255.158	4761.1	4747.4	547.32	0.04	1.09	4740.1	13.92	0.2137	27848.
21	257.984	258.128	4749.9	4738.1	547.51	0.04	1.08	4730.3	13.92	0.2173	27658.
22	260.995	261.139	4741.8	4726.6	547.57	0.06	1.08	4721.3	13.93	0.2025	27670.
23	263.964	264.150	4730.2	4718.3	547.65	0.05	1.08	4710.6	13.93	0.2169	27670.
24	266.975	267.119	4720.7	4708.0	547.73	0.03	1.08	4700.7	13.93	0.1970	27658.
25	269.986	270.130	4710.7	4698.2	547.89	0.05	1.11	4691.1	13.87	0.2165	27670.

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LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 14A
TEST DATE 7-15-82

PROCESSING DATE 7-21-82
TEST DURATION, SEC 148.00

HYBRID BEARING DATA
PUMP - END (PAGE 1)

TIME SLICE NO	PUMP BRG SUPPLY U/S PRESS (PSIA)	PUMP BRG SUPPLY TEMP (DEG R)	PUMP BRG SUPPLY D/S ORIF PRESS (PSIA)	PUMP BRG SUPPLY ORIF DP (PSID)	PUMP BRG SUPPLY MANIF PRESS (PSIA)	--- PUMP BRG PAD PRESSURES --- 3.00 OCLOCK (PSIA)	9.00 OCLOCK (PSIA)	6.30 OCLOCK (PSIA)
1	105.0	56.2	109.8	0.7	112.3	111.0	109.1	4.6
2	136.3	51.2	136.9	4.5	146.8	116.3	113.5	4.5
3	164.1	47.5	160.0	9.3	173.4	119.3	115.0	4.3
4	194.4	47.4	186.5	12.7	195.8	129.3	122.3	4.3
5	193.9	47.2	185.9	13.1	196.0	129.2	121.8	4.4
6	193.3	47.1	185.0	12.9	195.6	128.7	121.1	4.5
7	194.1	47.1	185.7	12.9	196.2	129.1	121.4	4.5
8	193.7	46.7	186.3	12.9	196.9	129.6	121.7	4.7
9	191.9	46.7	184.2	12.8	194.7	127.8	119.6	4.7
10	194.5	46.8	186.3	12.8	196.8	129.3	121.6	4.9
11	195.0	46.5	186.8	12.7	197.8	130.0	122.0	4.7
12	193.4	46.6	185.1	12.7	195.8	128.9	121.2	4.8
13	193.8	46.6	185.5	12.7	195.9	128.9	121.2	4.5
14	194.6	46.5	186.9	12.6	197.8	130.3	122.7	4.6
15	196.8	46.4	188.9	12.8	199.2	130.5	122.7	4.5
16	198.5	46.5	190.6	13.0	200.9	130.6	122.8	4.5
17	186.5	46.4	190.2	11.3	190.8	128.4	121.7	4.5
18	184.8	46.4	178.9	10.8	189.5	128.6	122.1	4.5
19	181.5	46.3	175.9	10.5	185.3	126.4	119.9	4.6
20	181.4	46.4	175.8	10.4	186.5	126.8	120.2	4.7
21	181.6	46.3	176.3	10.4	186.7	127.8	121.3	4.4
22	181.3	46.2	175.6	10.2	185.3	126.9	120.7	4.5
23	180.5	46.3	174.4	10.0	185.2	126.0	119.3	4.9
24	181.0	46.2	175.5	10.1	186.0	126.7	120.5	4.5
25	181.8	46.3	176.4	10.1	186.7	127.7	121.1	4.7

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 14
TEST DATE 7-15-82

PROCESSING DATE 7-21-82
TEST DURATION, SEC 148.00

HYBRID BEARING DATA
PUMP - END (PAGE 2)

TIME SLICE NO	PUMP BRG SUMP PRESSURE (PSIA)	PUMP BRG SUMP OUT PRESSURE (PSIA)	PUMP BRG SUMP OUT TEMP (DEG R)	SHAFT SPEED (RPM)	CARTRIDGE SPEED (RPM)	PUMP BRG FLOW (LB/SEC)	LH2 DENSITY AT ORIF (PCF)	AVERAGE PAD PRESSURE (PSIA)	PUMP BRG PRESSURE RATIO
1	108.2	50.7	41.8	1048.	129.	0.0066	0.4780	110.0	0.1673
2	109.5	53.6	44.7	16852.	541.	0.0461	3.7041	114.9	0.1452
3	105.4	53.6	44.5	24680.	3131.	0.0688	3.9996	117.2	0.1811
4	105.6	54.8	44.9	29745.	28606.	0.0807	4.0352	125.8	0.2213
5	104.8	53.5	44.5	29783.	29771.	0.0820	4.0509	125.5	0.2275
6	104.4	53.7	44.6	29783.	29765.	0.0814	4.0545	124.9	0.2252
7	104.8	53.6	44.5	29879.	29870.	0.0816	4.0560	125.2	0.2236
8	105.2	53.3	44.2	29783.	29745.	0.0817	4.0731	125.7	0.2232
9	103.2	53.5	44.1	29783.	29724.	0.0813	4.0740	123.7	0.2241
10	104.7	54.0	44.2	29855.	29840.	0.0815	4.0730	125.5	0.2258
11	105.4	53.9	44.0	29783.	29736.	0.0811	4.0855	126.0	0.2230
12	104.1	52.5	44.2	29802.	29764.	0.0812	4.0798	125.0	0.2286
13	[illegible]	53.5	44.5	29801.	29774.	0.0811	4.0811	125.1	0.2283
14	[illegible]	53.9	44.5	29783.	29730.	0.0810	4.0872	126.5	0.2266
15	[illegible]	53.4	44.5	30288.	30274.	0.0815	4.0946	126.6	0.2334
16	103.5	52.1	44.1	30701.	30659.	0.0822	4.0877	126.7	0.2385
17	105.0	52.0	43.9	28534.	28477.	0.0766	4.0871	125.1	0.2334
18	106.1	52.0	43.9	28096.	28089.	0.0747	4.0828	125.3	0.2310
19	104.3	[illegible]	43.8	27862.	27795.	0.0737	4.0849	123.1	0.2296
20	104.6	51.7	43.9	27848.	27771.	0.0733	4.0799	123.5	0.2304
21	105.9	51.6	43.8	27658.	27588.	0.0725	4.0853	124.6	0.2310
22	105.0	51.4	43.6	27670.	27624.	0.0728	4.0918	123.8	0.2314
23	104.1	51.5	43.9	27670.	27597.	0.0721	4.0823	122.6	0.2285
24	105.0	51.5	43.7	27658.	27570.	0.0724	4.0887	123.6	0.2293
25	105.7	51.7	43.8	27670.	27633.	0.0722	4.0861	124.4	0.2305

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

PAGE 14. R

RUN NUMBER 14 A
TEST DATE 7-15-82

PROCESSING DATE 7-21-82
TEST DURATION, SEC 148.00

H Y B R I D B E A R I N G D A T A
PUMP - END (PAGE 3)

TIME SLICE NO	BRG DELTA P ORIFICE PSID	BRG DELTA P FILM PSID	BPG DELTA P TOTAL PSID	ORIFICE RESISTANCE SFC**2/ LB-IN**2	FLUID FILM RESISTANCE SFC**2/ LB-IN**2	POISEUILLE RENOLDS NO	COUETTE RENOLDS NO	LAMBDA BRG NO	TORQUE FLUID FILM (TEMP) IN-LBS
1	9.3	1.9	11.1	214369.9	43054.6	5253360.	78.	0.00002	-876.5297
2	31.9	5.4	37.3	5024.5	2553.1	8475666.	7496.	0.00392	-15.0236
3	53.2	11.8	65.0	11256.7	2489.1	10571761.	19162.	0.01207	-3.6119
4	71.0	20.2	91.2	10906.5	3099.2	13428852.	27687.	0.01666	-2.5752
5	70.5	20.7	91.2	10474.7	3084.3	13011286.	28478.	0.01777	-2.5684
6	70.6	20.5	91.2	10648.1	3095.6	12944733.	28422.	0.01786	-2.4013
7	71.0	20.5	91.4	10654.4	3069.1	12955154.	28499.	0.01789	-2.4761
8	71.2	20.5	91.7	10681.5	3070.0	12719346.	28149.	0.01798	-2.4610
9	71.0	20.5	91.5	10740.0	3101.4	12679626.	28118.	0.01818	-2.4821
10	71.3	20.8	92.1	10732.2	3130.6	12780927.	28241.	0.01805	-2.4804
11	71.8	20.6	92.4	10906.1	3130.6	12633116.	27984.	0.01805	-2.4565
12	70.8	21.0	91.8	10751.0	3185.2	12625820.	28075.	0.01818	-2.3779
13	70.8	21.0	91.8	10781.6	3189.3	12610599.	28071.	0.01820	-2.1075
14	71.3	20.9	92.2	10863.8	3183.8	12565484.	27945.	0.01808	-2.0480
15	72.6	22.1	94.7	10927.0	3327.2	12741852.	28320.	0.01843	-1.9804
16	74.2	23.2	97.4	10977.2	3438.3	13193734.	28749.	0.01844	-2.4015
17	65.7	20.0	85.8	11216.2	3415.2	11756353.	26807.	0.01788	-2.3839
18	64.1	19.3	83.4	11485.4	3449.8	11516642.	26512.	0.01768	-2.3704
19	63.1	18.8	81.9	11618.9	3463.6	11303165.	26219.	0.01780	-2.3188
20	63.0	18.9	81.9	11738.9	3514.1	11366620.	26257.	0.01770	-2.3481
21	62.1	18.7	80.8	11810.8	3547.0	11148072.	26024.	0.01763	-2.3512
22	62.4	18.8	81.2	11764.4	3541.3	11116922.	25976.	0.01778	-2.3766
23	62.6	18.5	81.1	12045.3	3568.3	11239018.	26076.	0.01773	-2.2833
24	62.4	18.6	81.0	11911.9	3543.4	11135349.	25968.	0.01772	-2.3312
25	62.3	18.7	81.0	11946.1	3578.0	11158594.	26056.	0.01767	-2.3077

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 14A
TEST DATE 7-15-82

PROCESSING DATE 7-21-82
TEST DURATION, SEC 148.00

HYBRID BEARING DATA
PUMP AND TURBINE END (PAGE 4)

	PUMP			TURBINE					
TIME SLICE NO	HS BRG CLEARANCE RADIAL IN	VISCOSITY PUMP BRG LB-HR/FT**2 * E10	CSUBP PUMP BRG BTU/ LB-R	HS BRG CLEARANCE RADIAL IN	VISCOSITY TURB BRG LB-HR/FT**2 * E10	CSUBP TURB BRG BTU/ LB-R	POISEUILLE RENOLDS NO	COUETTE RENOLDS NO	LAMBDA TURB NO
1	0.00246	0.11275	4.6931	0.00246	0.46524	4.0367	-17286.	0.	0.0000
2	0.00244	0.43355	4.4633	0.00246	0.46920	3.7017	14483121.	1168.	0.0005
3	0.00239	0.51515	3.4573	0.00244	0.54286	3.0988	22504724.	8042.	0.0028
4	0.00233	0.52000	3.4120	0.00243	0.54161	3.0603	32393408.	10187.	0.0027
5	0.00232	0.52634	3.3639	0.00243	0.54194	3.0575	32647487.	10370.	0.0027
6	0.00232	0.52785	3.3530	0.00244	0.53986	3.0577	32887166.	9517.	0.0025
7	0.00232	0.52822	3.3500	0.00244	0.53952	3.0732	33361959.	8859.	0.0023
8	0.00232	0.53553	3.2970	0.00244	0.54688	3.0343	32382357.	8781.	0.0023
9	0.00232	0.53587	3.2955	0.00244	0.54737	3.0331	32078223.	8682.	0.0023
10	0.00232	0.53512	3.2999	0.00244	0.54588	3.0338	32511140.	8713.	0.0023
11	0.00232	0.54028	3.2637	0.00244	0.54937	3.0231	32040842.	8669.	0.0023
12	0.00232	0.53817	3.2788	0.00244	0.54946	3.0224	32094022.	8718.	0.0023
13	0.00232	0.53856	3.2760	0.00244	0.55082	3.0161	32120999.	7510.	0.0020
14	0.00232	0.54129	3.2565	0.00244	0.55394	3.0017	31925456.	6729.	0.0018
15	0.00231	0.54361	3.2407	0.00245	0.55578	2.9997	32789385.	6166.	0.0016
16	0.00231	0.54008	3.2647	0.00245	0.55502	2.9909	33468932.	5667.	0.0014
17	0.00233	0.54385	3.2397	0.00244	0.55124	3.0257	29474221.	6571.	0.0019
18	0.00233	0.54282	3.2466	0.00244	0.55623	3.0066	27801685.	7165.	0.0021
19	0.00233	0.54418	3.2383	0.00244	0.55591	3.0092	27597358.	7626.	0.0023
20	0.00234	0.54228	3.2511	0.00244	0.55268	3.0255	27652716.	8170.	0.0024
21	0.00234	0.54480	3.2336	0.00244	0.55596	3.0061	26963001.	8118.	0.0025
22	0.00234	0.54735	3.2168	0.00244	0.55572	3.0120	27093582.	8100.	0.0025
23	0.00234	0.54333	3.2443	0.00244	0.55390	3.0219	27014324.	8204.	0.0025
24	0.00234	0.54614	3.2250	0.00244	0.55591	3.0367	26897982.	8115.	0.0025
25	0.00234	0.54502	3.2322	0.00244	0.55776	3.0022	26903916.	8094.	0.0025

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 14[illegible]
TEST DATE 7-15-82

PROCESSING DATE 7-31-82
TEST DURATION, SEC 148.00

H Y B R I D B E A R I N G D A T A
TURBINE END (PAGE 1)

TIME SLICE NO	TURB BRG SUPPLY U/S PRESS (PSIA)	TURB BRG SUPPLY U/S TEMP (DEG R)	TURB BRG SUPPLY D/S ORIF PRESS (PSIA)	TURB BRG SUPPLY ORIF DP (PSID)	TURB BRG SUPPLY MANIF PRESS (PSIA)	TURB BRG DISCH PRESS (PSIA)	TURB BRG SUMP PRESS (PSIA)	-- TURBINE BRG -- DISCHARGE LINE PRESS (PSIA)	TEMP (DEG R)
1	80.4	49.3	82.5	3.4	85.0	102.6	85.9	39.7	42.3
2	213.2	50.7	210.5	10.6	204.5	171.4	151.3	62.6	47.1
3	351.2	48.8	341.8	19.2	324.7	240.4	218.3	70.9	48.4
4	476.8	50.3	462.2	27.1	435.5	303.3	280.8	85.8	50.3
5	478.7	50.3	464.3	26.2	436.9	353.9	280.6	85.8	50.3
6	477.1	50.4	463.0	25.4	435.6	302.9	280.8	86.1	50.4
7	479.4	50.5	464.9	25.6	437.8	304.8	280.8	86.4	50.4
8	478.0	50.1	463.6	25.6	435.9	334.0	280.8	85.3	50.2
9	477.1	50.0	462.8	25.5	434.9	302.2	280.1	85.4	50.2
10	479.3	50.1	464.5	25.8	437.5	304.9	280.8	85.8	50.2
11	478.3	49.9	463.8	25.5	436.8	304.8	281.3	85.2	50.1
12	477.5	49.9	462.8	25.5	435.6	333.2	280.8	85.5	50.2
13	477.9	49.8	462.8	25.3	435.6	303.1	280.8	85.2	50.1
14	477.8	49.7	462.8	25.5	436.6	304.1	280.8	84.7	50.1
15	489.9	49.7	474.8	25.7	447.2	309.7	286.5	85.4	50.2
16	501.2	49.9	485.6	26.2	455.5	315.3	293.0	86.9	50.3
17	443.6	49.5	430.5	22.7	406.3	287.2	263.7	81.0	49.6
18	433.8	49.1	420.5	22.8	396.7	282.9	260.1	80.0	49.4
19	426.3	49.0	414.2	22.6	390.3	277.8	254.6	79.0	49.3
20	424.8	49.2	412.2	22.1	389.3	277.7	254.3	79.2	49.3
21	422.1	48.9	4C	22.3	387.2	276.8	254.1	78.5	49.2
22	422.7	49.0	4	22.2	387.2	276.5	253.9	78.7	49.2
23	420.5	49.1	[illegible]	22.0	384.5	274.7	252.2	78.3	49.2
24	420.9	48.9	409.1	21.7	386.9	275.5	254.1	78.4	49.2
25	423.1	48.9	409.8	22.0	387.2	277.8	254.1	78.6	49.2

ORIGINAL PAGE IS
OF POOR QUALITY

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 14A
TEST DATE 7-15-82

PROCESSING DATE 7-21-82
TEST DURATION, SEC 148.00

HYBRID BEARING DATA
TURBINE END (PAGE 2)

TIME SLICE NO	SHAFT SPEED (RPM)	TURBINE CARTRIDGE SPEED (RPM)	TURBINE H/S BRG FLOW (LB/SEC)	LH2 DENSITY AT ORIF (PCF)	TURB BRG SUPPLY MANIF PRESS (PSIA)	TURB BRG DISCH PRESS (PSIA)	TURB BRG SUMP PRESS (PSIA)	HYDROSTATIC BEARING DELTA PRESS (PSID)
1	1048.	2.	0.0565	3.769	85.0	102.6	85.9	-0.86
2	16852.	1097.	0.1011	3.858	204.5	171.4	151.3	53.24
3	24680.	8293.	0.1408	4.105	324.7	240.4	218.3	106.33
4	29745.	10581.	0.1678	4.134	435.5	303.3	280.8	154.77
5	29783.	10779.	0.1648	4.136	436.9	333.9	280.6	156.27
6	29783.	9858.	0.1624	4.129	436.6	302.9	280.8	155.86
7	29879.	9156.	0.1627	4.128	437.8	304.8	280.8	157.06
8	29783.	9153.	0.1632	4.147	436.9	304.0	280.8	156.14
9	29783.	9051.	0.1631	4.148	434.9	302.2	280.1	154.82
10	29855.	9081.	0.1639	4.148	437.5	304.9	280.8	156.72
11	29783.	9057.	0.1632	4.153	436.8	334.8	281.3	155.53
12	29802.	9110.	0.1629	4.153	436.6	303.2	280.8	155.86
13	29801.	7846.	0.1624	4.156	436.6	303.1	280.8	155.86
14	29783.	7046.	0.1634	4.163	436.6	304.1	280.8	155.86
15	30288.	6467.	0.1640	4.171	447.2	309.7	286.5	160.68
16	30701.	5939.	0.1656	4.172	456.5	315.0	293.0	163.47
17	28534.	6852.	0.1539	4.148	406.3	287.2	263.7	142.54
18	28096.	7513.	0.1543	4.158	396.7	282.9	260.1	136.61
19	27862.	7996.	0.1536	4.156	390.3	277.8	254.6	135.67
20	27848.	8543.	0.1516	4.147	389.3	277.7	254.3	134.98
21	27658.	8525.	0.1525	4.156	387.2	276.8	254.1	133.19
22	27670.	8495.	0.1520	4.154	387.2	276.5	253.9	133.36
23	27670.	8588.	0.1514	4.149	384.5	274.7	252.2	132.32
24	27658.	8522.	0.1506	4.155	386.9	275.5	254.1	132.85
25	27670.	8507.	0.1516	4.159	387.2	277.8	254.1	133.19

RUN NUMBER 14 B
TEST DATE 7-15-82

PROCESSING DATE 7-21-82
TEST DURATION, SEC 148.00

COMMENTS . . .
TEST 148

AMBIENT PRESSURE		13.8000
LO2 VENTURI (GG) P/N V160248-SGR S/N 8871	UPSTREAM DIAMETER	0.0
	THROAT DIAMETER	0.0
	THROAT CD	0.0
GH2 VENTURI (TURB) P/N VP031200-SGR S/N 9731	UPSTREAM DIAMETER	2.3000
	THROAT DIAMETER	1.3085
	THROAT CD	0.9875
LH2 VENTURI (GG) P/N V320471-SGR S/N 8873	UPSTREAM DIAMETER	0.0
	THROAT DIAMETER	0.0
	THROAT CD	0.0
LH2 VENTURI (PUMP DISCH) P/N V320709-SGR S/N 8874	UPSTREAM DIAMETER	1.6890
	THROAT DIAMETER	0.7090
	THROAT CD	0.9760
	TURBINE SYSTEM EFF. AREA	0.70470
	TURBINE EXHAUST ORIFICE 4 EACH	0.31200
	4 EACH	0.32500
	1 EACH	0.30800
	4 EACH	0.37500
	4 EACH	0.31250
	TURBINE EXHAUST EFF. AREA	1.28100

HYDROSTATIC BEARING SUPPLY SYSTEM
TURBINE INLET DUCT DIA 0.334 ORIFICE DIA 0.194
PUMP INLET DUCT DIA 0.402 ORIFICE DIA 0.175

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 14
TEST DATE 7-15-82

PROCESSING DATE 7-21-82
TEST DURATION, SEC 148.00

G A S E O U S   H Y D R O G E N   T U R B I N E   D R I V E   P A R A M E T E R S

TIME SLICE NO	BEGIN TIME (SEC)	END TIME (SEC)	REG U/S PR (PSIA)	VENTURI U/S PR (PSIA)	VENTURI U/S TEMP (DEG R)	VENTURI DELTA PR (PSID)	SPIN VALVE POSN	SPIN VALVE U/S PR (PSIA)	FAC DUCT PR (PSIA)	TURB GH2 FLOW (LB/SEC)	SPEED (RPM)
1	269.986	270.130	4710.7	4698 2	547.89	0.84	1.11	4691.1	13.87	0.2165	27670.
2	270.976	271.161	4706.1	469 6	547.99	0.54	4.19	4683.5	13.93	0.7937	39845.
3	271.966	272.151	4693.2	4679.7	548.53	1.89	8.16	4667.7	13.93	1.4866	52150.
4	272.997	273.141	4673.8	4657.8	549.42	5.19	13.99	4636.8	19.60	2.4534	65528.
5	273.987	274.131	4647.7	4630.7	550.35	7.44	16.95	4604.8	24.26	2.9275	71994.
6	274.976	275.121	4619.4	4601.9	551.18	8.16	17.86	4573.9	25.54	3.0565	73621.
7	275.966	276.152	4590.1	4572.5	551.63	8.45	18.27	4543.9	25.99	3.1015	74161.
8	276.997	277.142	4560.6	4542.7	551.80	8.59	18.48	4514.3	26.19	3.1177	74426.
9	277.987	278.132	4531.8	4514.1	551.85	8.63	18.61	4485.4	26.16	3.1171	74522.
10	278.977	279.121	4503.1	4485.3	551.83	8.67	18.72	4456.0	26.21	3.1155	74432.
11	279.967	280.153	4473.9	4457.0	551.75	8.72	18.87	4426.9	26.32	3.1166	74502.
12	284.999	285.143	4332.0	4314.6	551.21	8.99	19.47	4283.9	26.41	3.1224	74450.
13	289.989	290.134	4192.9	4175.9	550.66	9.35	20.31	4143.7	26.61	3.1436	74690.
14	294.980	295.124	4053.1	4035.7	549.84	10.23	21.77	4000.5	27.62	3.2431	75740.
15	299.971	300.156	3911.4	3893.8	548.84	11.31	23.37	3855.0	28.77	3.3608	76837.
16	304.961	305.147	3771.9	3753.4	547.44	11.71	24.33	3713.6	28.89	3.3715	76885.
17	309.993	310.137	3633.2	3615.2	545.85	12.16	25.30	3573.6	28.89	3.3860	76863.
18	314.984	315.128	3498.7	3481.3	544.08	12.57	26.31	3438.1	28.90	3.3925	76863.
19	319.974	320.160	3365.8	3348.4	542.15	13.01	27.41	3304.1	28.94	3.4003	76827.
20	324.965	325.190	3236.7	3219.1	540.00	13.49	28.57	3173.0	28.93	0.0	76846.
21	329.997	330.141	3110.0	3093.6	537.68	14.08	29.80	3045.6	28.90	3.6179	76749.
22	334.987	335.131	2985.8	2969.2	535.22	14.60	31.14	2920.4	28.97	3.6038	76737.
23	339.978	340.122	2864.7	2848.0	532.51	15.25	32.55	2797.2	28.95	3.6008	76725.

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 148
TEST DATE 7-15-82

PROCESSING DATE 7-21-82
TEST DURATION, SEC 140.00

HYBRID BEARING DATA
PUMP - END (PAGE 1)

TIME SLICE NO	PUMP BRG SUPPLY U/S PRESS (PSIA)	PUMP BRG SUPPLY TEMP (DEG R)	PUMP BRG SUPPLY D/S ORIF PRESS (PSIA)	PUMP BRG SUPPLY ORIF DP (PSID)	PUMP BRG SUPPLY MANIF PRESS (PSIA)	--- PUMP BRG PAD PRESSURES --- 3.00 OCLOCK (PSIA)	9.00 OCLOCK (PSIA)	6.30 OCLOCK (PSIA)
1	181.8	46.3	176.4	10.1	186.7	127.7	121.1	4.7
2	266.4	46.8	250.0	20.5	260.1	140.7	135.8	4.7
3	394.5	49.0	367.6	29.2	377.7	172.3	170.0	4.8
4	583.4	52.7	547.0	39.6	557.8	277.2	287.0	4.5
5	689.7	55.5	645.8	45.0	657.9	328.3	334.0	4.4
6	719.6	56.3	674.6	46.3	684.6	333.7	343.1	4.5
7	734.1	56.5	689.1	45.3	701.7	355.6	362.4	4.4
8	731.5	56.6	685.9	47.7	698.3	361.2	358.7	4.5
9	712.1	57.0	653.6	60.2	665.4	256.9	235.7	4.7
10	733.2	56.8	686.3	49.0	698.3	336.6	338.0	4.5
11	738.6	56.8	694.8	45.7	707.3	367.1	367.9	4.5
12	738.6	56.8	695.5	45.4	708.3	374.9	367.6	4.5
13	743.8	56.8	700.0	46.0	712.8	387.0	382.3	4.6
14	762.2	57.2	717.2	45.6	730.6	401.7	392.6	4.5
15	783.0	57.6	736.1	47.4	748.6	414.7	404.0	4.5
16	779.2	57.6	730.9	48.8	743.9	411.2	398.0	4.6
17	783.3	57.6	736.9	46.8	749.3	420.2	407.9	4.3
18	772.3	57.7	721.6	51.2	733.6	376.2	365.0	4.3
19	774.5	57.6	724.5	49.6	737.4	404.1	390.0	4.1
20	778.4	57.6	732.2	46.1	745.3	416.5	400.2	4.2
21	778.9	57.6	732.7	44.9	745.7	422.3	405.4	4.3
22	780.1	57.5	734.3	44.4	747.7	428.3	417.7	4.1
23	777.4	57.6	732.3	43.5	745.8	424.2	409.1	4.1

RUN NUMBER 148
TEST DATE 7-15-82

PROCESSING DATE 7-21-82
TEST DURATION, SEC 148.00

H Y B R I D   B E A R I N G   D A T A
PUMP - END (PAGE 2)

TIME SLICE NO	PUMP BRG SUMP PRESSURE (PSIA)	PUMP BRG SUMP OUT PRESSURE (PSIA)	PUMP BRG SUMP OUT TEMP (DEG R)	SHAFT SPEED (RPM)	CARTRIDGE SPEED (RPM)	PUMP BRG FLOW (LB/SEC)	LH2 DENSITY AT ORIF (PCF)	AVERAGE PAD PRESSURE (PSIA)	PUMP BRG PRESSURE RATIO
1	105.7	51.7	43.8	27670.	27633.	0.0722	4.0861	124.4	0.2305
2	102.6	53.3	44.6	39845.	30418.	0.1036	4.1321	138.2	0.2263
3	100.2	60.9	46.8	52150.	34303.	0.1238	4.1322	171.1	0.2555
4	98.7	65.5	47.5	65528.	57353.	0.1437	4.1057	282.[illegible]	0.3995
5	97.9	66.8	47.6	71904.	55083.	0.1524	4.0613	331.1	0.4165
6	98.2	68.8	47.9	73621.	54113.	0.1543	4.0504	338.4	0.4082
7	98.8	69.1	48.0	74161.	58437.	0.1526	4.0510	359.0	0.4315
8	96.9	69.0	48.0	74426.	55627.	0.1565	4.0472	360.0	0.4374
9	99.2	67.9	47.9	74522.	8272.	0.1752	4.0137	246.3	0.2598
10	99.7	70.3	48.1	74432.	54626.	0.1585	4.0382	337.3	0.3970
11	99.2	69.5	48.0	74507.	58866.	0.1531	4.0421	367.5	0.4412
12	97.6	68.8	48.0	74450.	60049.	0.1527	4.0452	371.2	0.4481
13	99.0	69.8	48.1	74690.	59885.	0.1538	4.0484	384.6	0.4654
14	97.3	70.1	48.2	75740.	61651.	0.1530	4.0449	397.2	0.4735
15	99.0	71.3	48.3	76837.	63453.	0.1561	4.0433	409.4	0.4779
16	98.4	71.2	48.3	76885.	61701.	0.1581	4.0383	404.6	0.4744
17	98.4	71.4	48.3	76863.	64017.	0.1550	4.0422	414.1	0.4850
18	98.2	70.4	48.1	76863.	55971.	0.1618	4.0287	370.6	0.4287
19	98.8	71.3	48.2	76827.	56804.	0.1594	4.0364	397.0	0.4670
20	98.8	71.5	48.3	76846.	62658.	0.1538	4.0377	408.3	0.4769
21	97.2	70.9	48.2	76749.	63611.	0.1517	4.0390	413.8	0.4883
22	98.8	71.0	48.2	76737.	63274.	0.1509	4.0434	423.0	0.4996
23	97.9	71.3	48.2	76725.	62841.	0.1494	4.0378	416.6	0.4919

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 148
TEST DATE 7-15-82

PROCESSING DATE 7-21-82
TEST DURATION, SEC 148.00

H Y B R I D B E A R I N G D A T A
PUMP - END (PAGE 3)

TIME SLICE NO	BRG DELTA P ORIFICE PSID	BRG DELTA P FILM PSID	BRG DELTA P TOTAL PSID	ORIFICE RESISTANCE SEC**2/ LB-IN**2	FLUID FILM RESISTANCE SEC**2/ LB-IN**2	POISEUILLE RENOLDS NO	COUETTE RENOLDS NO	LAMBDA BRG NO	TORQUE FLUID FILM (TEMP) IN-LBS
1	62.3	18.7	81.0	11946.1	3578.0	11158594.	26056.	0.01767	-2.3077
2	121.9	35.6	157.5	11356.6	3321.2	21505859.	28591.	0.01405	-3.1411
3	206.5	70.9	277.4	13480.2	4627.2	40166837.	32949.	0.01051	-3.8091
4	275.7	183.4	459.0	13351.6	8881.2	48128527.	48831.	0.01457	-5.3530
5	326.8	233.3	560.1	14069.2	10042.4	67052838.	48290.	0.01070	-8.4248
6	348.3	240.2	588.5	14627.9	10088.6	73870727.	47914.	0.00970	-9.1347
7	342.7	260.2	602.9	14710.9	11166.1	67892284.	49832.	0.01100	-8.5606
8	339.3	263.0	601.3	13813.6	10738.6	72189849.	48412.	0.01008	-9.2090
9	419.0	147.1	566.1	13657.3	4793.5	168681635.	9820.	0.00096	-71.9333
10	360.9	237.6	598.5	14368.6	9458.3	76027867.	48324.	0.00950	-9.6027
11	339.8	268.3	608.1	14500.7	11447.1	67959619.	49958.	0.01103	-8.7145
12	337.0	273.6	610.6	14448.2	11730.5	65818514.	50368.	0.01151	-8.5228
13	328.2	285.7	613.8	13870.8	12074.5	65552416.	50099.	0.01148	-8.5358
14	333.5	299.9	633.4	14244.0	12809.9	64853183.	50669.	0.01182	-8.5272
15	339.2	310.4	649.6	13923.8	12742.8	63669943.	51248.	0.01219	-8.6979
16	339.3	306.3	645.6	13573.1	12250.6	66686160.	50669.	0.01150	-9.0483
17	335.2	315.7	650.9	13955.8	13142.9	62585654.	51357.	0.01244	-8.5894
18	363.0	272.4	635.5	13864.5	10404.8	78295775.	48586.	0.00938	-10.4753
19	340.4	298.2	638.6	13388.2	11728.8	74705983.	48635.	0.00984	-9.9328
20	336.9	309.6	646.5	14246.6	13090.5	64905658.	50981.	0.01189	-8.6402
21	331.9	316.7	648.6	14422.1	13760.6	63026005.	51194.	0.01232	-8.4745
22	324.7	324.2	648.9	14251.9	14230.3	62834129.	50932.	0.01227	-8.4175
23	329.2	318.7	648.0	14759.8	14289.3	64083514.	50886.	0.01204	-8.4439

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MK4A-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 148
TEST DATE 7-15-82

PROCESSING DATE 7-21-82
TEST DURATION, SEC 148.00

HYBRID BEARING DATA
PUMP AND TURBINE END (PAGE 4)

	PUMP			TURBINE					
TIME SLICE NO	HS BRG CLEARANCE RADIAL IN	VISCOSITY PUMP BRG LB-HR/FT**2 * E10	CSUBP PUMP BRG BTU/ LB-R	HS BRG CLEARANCE RADIAL IN	VISCOSITY TURB BRG LB-HR/FT**2 * E10	CSUBP TURB BRG BTU/ LB-R	POISEUILLE RENOLDS NO	COUETTE RENOLDS NO	LARSCA TURB NO
1	0.00234	0.54502	3.2322	0.00244	0.55776	3.0022	26903916.	8094.	0.0025
2	0.00231	0.53779	3.2751	0.00244	0.56976	2.8756	54216992.	6588.	0.0011
3	0.00228	0.50274	3.5169	0.00245	0.54934	2.8879	97877097.	3462.	0.0003
4	0.00199	0.47108	3.7393	0.00246	0.53674	2.9044	160124278.	182.	0.0000
5	0.00203	0.43941	4.0350	0.00246	0.51856	2.9376	206495425.	1.	0.0000
6	0.00204	0.42918	4.1514	0.00246	0.51225	2.9485	219554158.	1.	0.0000
7	0.00198	0.43201	4.0838	0.00246	0.51013	2.9514	224408351.	1.	0.0000
8	0.00202	0.43165	4.0869	0.00246	0.50836	2.9546	226806663.	1.	0.0000
9	0.00244	0.34852	5.3140	0.00246	0.50510	2.9637	228837931.	1.	0.0000
10	0.00203	0.42066	4.2720	0.00246	0.50643	2.9596	227634583.	1.	0.0000
11	0.00197	0.43030	4.0933	0.00246	0.50608	2.9607	228416223.	1.	0.0000
12	0.00195	0.43264	4.0598	0.00246	0.50696	2.9578	228065654.	1.	0.0000
13	0.00195	0.43668	3.9964	0.00246	0.50768	2.9563	228805040.	1.	0.0000
14	0.00193	0.43452	4.0071	0.00246	0.50820	2.9567	234580095.	1.	0.0000
15	0.00190	0.43237	4.0181	0.00246	0.50919	2.9565	239678100.	1.	0.0000
16	0.00193	0.43001	4.0500	0.00246	0.50867	2.9579	240717384.	1.	0.0000
17	0.00189	0.43342	4.0015	0.00246	0.50941	2.9560	240238284.	1.	0.0000
18	0.00201	0.41730	4.2575	0.00246	0.50790	2.9602	240490804.	1.	0.0000
19	0.00200	0.42813	4.0810	0.00246	0.50908	2.9568	239740738.	1.	0.0000
20	0.00191	0.43123	4.0320	0.00246	0.50864	2.9579	239986983.	1.	0.0000
21	0.00189	0.43334	4.0026	0.00246	0.50856	2.9577	239973007.	1.	0.0000
22	0.00190	0.43760	3.9481	0.00246	0.50918	2.9563	239132274.	1.	0.0000
23	0.00191	0.43425	3.9899	0.00246	0.50814	2.9589	239582293.		

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OF POOR QUALITY

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

PAGE 14.10

RUN NUMBER 14 B
TEST DATE 7-15-82

PROCESSING DATE 7-21-82
TEST DURATION, SEC 148.00

H Y B R I D   B E A R I N G   D A T A
TURBINE END (PAGE 1)

TIME SLICE NO	TURB BRG SUPPLY U/S PRESS (PSIA)	TURB BRG SUPPLY U/S TEMP (DEG R)	TURB BRG SUPPLY D/S ORIF PRESS (PSIA)	TURB BRG SUPPLY ORIF DP (PSID)	TURB BRG SUPPLY MANIF PRESS (PSIA)	TURB BRG DISCH PRESS (PSIA)	TURB BRG SUMP PRESS (PSIA)	TURBINE BRG DISCHARGE LINE PRESS (PSIA)	TURBINE BRG DISCHARGE LINE TEMP (DEG R)
1	423.1	48.9	409.8	22.0	387.2	277.8	254.1	78.6	49.2
2	792.1	52.3	765.0	42.1	714.2	460.1	434.4	115.0	53.3
3	1314.5	59.2	1260.5	78.2	1172.4	717.9	691.2	171.6	57.8
4	2071.1	69.8	1987.1	112.7	1848.1	1092.2	1066.8	246.3	62.8
5	2529.4	77.4	2430.8	136.6	2259.2	1309.1	1283.2	315.2	69.0
6	2649.1	79.6	2547.2	145.4	2366.8	1368.5	1343.1	332.2	70.9
7	2692.5	[illegible]	2590.2	145.5	2406.5	1390.3	1365.2	338.8	71.7
8	2704.8	[illegible]	2601.3	145.0	2417.2	1395.0	1369.5	340.1	71.9
9	2714.2	81.3	2610.5	144.2	2425.6	1401.1	1376.2	342.2	72.3
10	2709.3	81.0	2605.1	141.9	2420.1	1398.5	1373.[illegible]	341.3	72.2
11	2713.8	81.2	2610.3	141.7	2425.5	1401.0	1375.9	341.8	72.2
12	2714.5	81.0	2610.7	140.8	2425.3	1400.5	1375.4	342.5	72.2
13	2731.3	81.2	2626.7	141.6	2439.8	1409.3	1383.9	345.0	72.5
14	2806.5	82.3	2699.5	142.7	2508.1	1444.4	1419.6	354.9	73.7
15	2890.4	83.5	2780.1	146.2	2582.7	1487.3	1463.2	364.7	75.0
16	2896.6	83.7	2785.8	147.8	2588.8	1490.0	1465.5	366.8	75.2
17	2897.0	83.6	2786.5	147.5	2589.7	1491.2	1466.6	366.1	75.1
18	2893.8	83.7	2783.5	147.7	2584.7	1489.2	1464.5	365.5	75.1
19	2890.5	83.5	2780.1	145.9	2582.4	1487.9	1462.9	366.3	75.0
20	2888.1	83.5	2778.3	146.1	2580.9	1485.9	1461.5	365.0	[illegible]
21	2885.1	83.5	2773.7	146.0	2576.6	1494.1	1457.8	365.0	75.0
22	2883.8	83.4	2771.8	145.9	2576.0	1484.0	1459.4	364.1	74.9
23	2879.1	83.5	2767.0	145.9	2571.3	1480.9	1455.6	363.3	74.9

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 14B
TEST DATE 7-15-82

PROCESSING DATE 7-21-82
TEST DURATION, SEC 148.00

HYBRID BEARING DATA
TURBINE END (PAGE 2)

TIME SLICE NO	SHAFT SPEED (RPM)	TURBINE CARTRIDGE SPEED (RPM)	TURBINE H/S BRG FLOW (LB/SEC)	LH2 DENSITY AT ORIF (PCF)	TURB BRG SUPPLY MANIF PRESS (PSIA)	TURB BRG DISCH PRESS (PSIA)	TURB BRG SUMP PRESS (PSIA)	HYDROSTATIC BEARING DELTA PRESS (PSID)
1	27670.	8507.	0.1516	4.159	387.2	277.8	254.1	133.19
2	39845.	7089.	0.2123	4.264	714.2	460.1	434.4	279.78
3	52150.	3703.	0.2907	4.303	1172.4	717.9	691.2	481.13
4	65528.	199.	0.3501	4.333	1848.1	1092.2	1066.8	781.27
5	71994.	1.	0.3848	4.319	2259.2	1309.1	1283.2	975.92
6	73621.	1.	0.3966	4.310	2366.8	1368.5	1343.1	1023.67
7	74161.	1.	0.3966	4.308	2406.5	1390.3	1365.2	1041.25
8	74426.	1.	0.3958	4.304	2417.2	1395.0	1369.5	1047.71
9	74522.	1.	0.3942	4.293	2425.6	1401.1	1376.2	1049.43
10	74432.	1.	0.3913	4.299	2420.1	1398.5	1373.7	1046.45
11	74502.	1.	0.3909	4.297	2425.5	1401.0	1375.9	1049.63
12	74450.	1.	0.3898	4.301	2425.3	1400.5	1375.4	1049.92
13	74690.	1.	0.3911	4.304	2439.8	1409.3	1383.9	1055.98
14	75740.	1.	0.3927	4.305	2508.1	1444.4	1419.6	1088.50
15	76837.	1.	0.3977	4.309	2582.7	1487.3	1463.2	1119.49
16	76885.	1.	0.3996	4.307	2588.8	1490.0	1465.5	1123.39
17	76863.	1.	0.3994	4.309	2589.7	1491.2	1466.6	1123.04
18	76863.	1.	0.3995	4.305	2584.7	1489.2	1464.5	1120.24
19	76827.	1.	0.3972	4.309	2582.4	1487.9	1462.9	1119.48
20	76846.	1.	0.3974	4.307	2580.9	1485.9	1461.5	1119.44
21	76749.	1.	0.3973	4.308	2576.6	1484.1	1457.8	1118.86
22	76737.	1.	0.3972	4.309	2576.0	1484.0	1459.4	1116.50
23	76725.	1.	0.3971	4.306	2571.3	1480.9	1455.6	1115.71

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 14C
TEST DATE 7-15-82

PROCESSING DATE 7-21-82
TEST DURATION, SEC 148.00

COMMENTS . . .
TEST 14C

AMBIENT PRESSURE		13.8000
LO2 VENTURI (GG) P/N V160240-SGR S/N 8871	UPSTREAM DIAMETER	0.0
	THROAT DIAMETER	0.0
	THROAT CD	0.0
GH2 VENTURI (TURB) P/N VP031200-SGR S/N 9731	UPSTREAM DIAMETER	2.3000
	THROAT DIAMETER	1.3085
	THROAT CD	0.9873
LH2 VENTURI (GG) P/N V320471-SGR S/N 8873	UPSTREAM DIAMETER	0.0
	THROAT DIAMETER	0.0
	THROAT CD	0.0
LH2 VENTURI (PUMP DISCH) P/N V320709-SGR S/N 8874	UPSTREAM DIAMETER	1.6890
	THROAT DIAMETER	0.7090
	THROAT CD	0.9760
	TURBINE SYSTEM EFF. AREA	0.70470
	TURBINE EXHAUST ORIFICE 4 EACH	0.31200
	4 EACH	0.32500
	1 EACH	0.30800
	4 EACH	0.37500
	4 EACH	0.31250
	TURBINE EXHAUST EFF. AREA	1.28100

HYDROSTATIC BEARING SUPPLY SYSTEM
TURBINE INLET DUCT DIA 0.334 ORIFICE DIA 0.194
PUMP INLET DUCT DIA 0.402 ORIFICE DIA 0.175

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MK48-
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 14C
TEST DATE 7-15-82

PROCESSING DATE 7-21-82
TEST DURATION, SEC 148.00

GASEOUS HYDROGEN TURBINE DRIVE PARAMETERS

TIME SLICE NO	BEGIN TIME (SEC)	END TIME (SEC)	PFC U/S PR (PSIA)	VENTURI U/S PR (PSIA)	VENTURI U/S TEMP (DEG R)	VENTURI DELTA PR (PSID)	SPIN VALVE PCSN	SPIN VALVE U/S PR (PSIA)	FAC DUCT PR (PSIA)	TURB GH2 FLOW (LB/SEC)	SPEED (RPM)
1	340.473	340.658	2951.5	2935.3	532.22	15.53	32.57	2785.5	29.21	3.4248	76875.
2	340.968	341.153	2838.7	2821.6	531.94	16.76	34.43	2766.5	30.43	3.7549	77908.
3	341.462	341.648	2825.2	2807.3	531.64	18.46	36.32	2748.6	32.90	3.[illegible]85	79397.
4	341.999	342.143	2811.3	2790.5	531.24	22.60	38.73	2726.1	34.09	4.1344	81168.
5	2.494	342.638	2795.7	2774.7	530.76	23.19	41.22	2703.8	36.29	4.3613	83059.
6	[illegible]2.989	343.133	2780.6	2758.8	530.37	24.77	43.01	2684.4	37.77	4.5004	84355.
7	[illegible]3.483	343.628	2764.8	2742.7	529.70	26.19	44.47	2666.2	38.30	4.6111	85052.
8	343.9[illegible]8	344.123	2749.0	2726.0	529.19	27.42	45.75	2646.0	39.85	4.7002	85676.
9	344.473	344.659	2732.1	2708.5	528.66	28.53	47.04	[illegible]5.4	40.90	4.7767	85338.
10	344.968	345.154	2715.2	2690.8	528.06	29.71	48.29	[illegible].9	41.70	4.8560	85842.
11	345.463	345.649	2699.6	2674.5	527.52	30.61	49.33	2586.3	42.09	4.9110	86572.
1[illegible]	345.958	346.144	2683.3	2657.4	526.98	31.32	50.17	2567.[illegible]	42.78	4.9499	866[illegible].
13	346.494	346.639	2698.0	2690.[illegible]	526.69	5.25	12.97	2471.9	18.99	2.0503	72294.
[illegible]	346.989	347.134	2688.4	2681.7	527.38	0.0	-1.16	2035.2	14.07	0.0007	52453.
15	347.484	347.629	2686.1	2678.2	528.14	0.0	-1.12	1031.0	14.02	0.0008	19247.
16	347.979	348.123	2682.5	2674.7	528.89	0.0	-1.05	574.4	14.03	0.0008	9175.
17	348.474	348.619	2680.5	2673.3	529.49	0.0	1.09	341.0	14.05	0.0008	5019.
18	348.969	349.155	2684.2	2677.5	530.00	0.0	-0.99	210.6	14.04	0.0009	2892.
19	349.464	349.649	2687.7	2680.1	530.45	0.0	-0.97	136.7	14.04	0.0009	1336.
20	349.959	350.144	2689.3	2682.3	530.79	0.0	-0.97	90.2	14.03	0.0009	1.
21	350.[illegible]95	350.639	2690.8	2683.3	531.23	0.0	-0.96	59.6	14.03	0.0009	1.
22	350.990	351.134	2690.2	2682.2	531.55	0.0	-0.96	39.9	14.03	0.0010	1.

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RUN NUMBER 14C
TEST DATE 7-15-82

PROCESSING DATE 7-21-82
TEST DURATION, SEC 140.00

H Y B R I D B E A R I N G D A T A
PUMP - END (PAGE 1)

TIME SLICE NO	PUMP BRG SUPPLY U/S PRESS (PSIA)	PUMP BRG SUPPLY TEMP (DEG R)	PUMP BRG SUPPLY D/S ORIF PRESS (PSIA)	PUMP BRG SUPPLY ORIF DP (PSID)	PUMP BRG SUPPLY MANIF PRESS (PSIA)	--- PUMP BRG PAD PRESSURES --- 3.00 OCLOCK (PSIA)	9.00 OCLOCK (PSIA)	6.30 OCLOCK (PSIA)
1	765.3	57.6	711.9	52.0	725.1	361.6	346.1	4.1
2	782.3	57.8	727.8	53.5	739.7	374.9	360.3	4.1
3	796.2	58.4	742.4	62.3	744.2	375.5	314.5	4.7
4	845.0	59.0	788.0	55.2	801.2	399.5	385.7	4.1
5	875.7	59.6	813.9	60.2	824.4	367.8	310.8	4.3
6	893.6	60.3	825.0	65.4	837.4	311.5	313.6	4.1
7	904.6	61.0	835.7	65.5	848.4	351.3	257.3	4.5
8	923.0	61.4	854.3	64.6	860.5	333.5	307.8	4.7
9	913.7	62.1	847.9	63.1	860.5	325.6	319.8	5.2
10	924.4	62.2	857.4	63.2	870.9	323.3	324.3	8.0
11	937.9	62.5	870.6	64.9	883.1	332.3	327.5	8.6
12	941.4	62.6	873.1	65.1	886.1	333.4	324.7	8.4
13	712.0	65.1	655.9	43.7	686.5	266.5	279.9	9.8
14	114.3	91.4	119.7	0.0	128.6	108.0	106.6	10.8
15	146.7	54.1	150.0	0.0	161.4	110.8	106.1	9.8
16	113.2	55.6	119.3	0.0	129.8	113.5	111.3	9.3
17	107.1	62.3	112.4	0.0	123.4	112.4	108.9	9.0
18	102.9	58.4	109.3	0.0	119.6	110.6	107.4	6.7
19	100.2	55.7	106.7	0.0	117.6	108.8	104.0	5.8
20	93.8	57.4	100.1	0.0	110.6	102.5	99.5	5.0
21	52.6	59.0	59.0	0.0	67.9	59.8	56.5	5.3
22	47.4	67.4	54.[illegible]	0.0	62.1	54.4	51.4	5.0

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 14C
TEST DATE 7-15-82

PROCESSING DATE 7-21-82
TEST DURATION, SEC 148.00

H Y B R I D   B E A R I N G   D A T A
PUMP - END (PAGE 2)

TIME SLICE NO	PUMP BRG SUMP PRESSURE (PSIA)	PUMP BRG SUMP OUT PRESSURE (PSIA)	PUMP BRG SUMP OUT TEMP (DEG R)	SHAFT SPEED (RPM)	CARTRIDGE SPEED (RPM)	PUMP BRG FLOW (LB/SEC)	LH2 DENSITY AT ORIF (PCF)	AVERAGE PAD PRESSURE (PSIA)	PUMP BRG PRESSURE RATIO
1	97.1	70.2	49.2	76875.	52022.	0.1631	4.0289	354.8	0.4104
2	96.7	70.5	48.2	77908.	58231.	0.1656	4.0311	367.6	0.4213
3	97.0	71.6	48.3	79397.	45839.	0.1782	4.0169	320.0	0.3445
4	97.3	74.3	48.7	81168.	52240.	0.1680	4.0285	392.6	0.4195
5	98.8	77.7	49.1	83059.	45963.	0.1754	4.0237	372.3	0.[illegible]
6	99.0	79.6	49.4	84355.	19432.	0.1825	4.0083	312.8	[illegible].284[illegible]
7	99.8	81.2	49.6	85952.	475.	0.1822	3.9882	304.3	0.2732
8	99.5	82.0	49.7	85676.	376.	0.1808	3.9859	320.6	0.2803
9	100.9	82.0	49.7	85138.	807.	0.1778	3.9492	322.7	0.2920
10	100.5	81.9	49.7	85847.	1141.	0.1781	3.9530	323.8	(0.2900)
11	101.6	82.1	49.8	86572.	795.	0.1804	3.9494	329.9	0.2922
12	101.4	82.9	49.8	86687.	363.	0.1807	3.9492	328.8	0.2898
13	130.4	107.4	51.7	72294.	2178.	0.1416	3.6126	271.2	0.2532
14	100.2	83.1	59.6	52453.	621.	0.0	0.2503	107.3	0.2504
15	101.7	68.3	47.9	19247.	2092.	0.0	3.4429	108.4	0.1[illegible]95
16	108.6	64.6	46.3	9125.	3937.	0.0	0.5535	112.4	0.1773
17	108.1	57.6	45.0	5019.	4043.	0.0	0.3977	110.7	0.1698
18	106.9	56.2	43.5	2892.	2730.	0.0	0.4272	109.0	0.1639
19	105.4	54.9	43.4	1336.	1796.	0.0	0.4539	107.4	0.1668
20	99.4	52.2	43.6	1.	186.	0.0	0.3901	101.0	0.1425
21	57.7	39.5	41.9	1.	10.	0.0	0.1907	58.2	0.0485
22	52.2	37.1	41.7	1.	24.	0.0	0.1407	52.9	0.0675

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 14C
TEST DATE 7-15-82

PROCESSING DATE 7-21-82
TEST DURATION, SEC 148.00

H Y B R I D   B E A R I N G   D A T A
PUMP - END (PAGE 7)

TIME SLICE NO	BRG DELTA P ORIFICE PSID	BRG DELTA P FILM PSID	BRG DELTA P TOTAL PSID	ORIFICE RESISTANCE SEC**2/ LB-IN**2	FLUID FILM RESISTANCE SEC**2/ LB-IN**2	POISEUILLE RENOLDS NO	COUETTE RENOLDS NO	LAMBDA BRG NO	TORQUE FLUID FILM (TEMP) IN-LBS
1	370.2	257.7	627.9	13909.6	9682.8	95044935.	46593.	0.00828	-11.1029
2	372.1	270.9	641.0	13576.5	9903.2	75752132.	49679.	0.00995	-10.3048
3	424.2	223.0	647.2	13359.8	9920.9	104072789.	42471.	0.00619	-14.6375
4	408.7	295.3	703.9	14490.9	10463.4	95951393.	46106.	0.00737	-12.5092
5	454.1	273.5	727.6	14756.4	9897.4	115313536.	41839.	0.00557	-15.0591
6	524.6	213.7	738.4	15759.1	6420.3	146709675.	16302.	0.00171	-38.1982
7	544.0	204.5	748.6	16390.2	6161.5	119249629.	266.	0.00004	-1611.3911
8	545.9	221.1	767.0	16693.8	6762.0	123752507.	232.	0.00003	-2064.2700
9	537.8	221.8	759.6	17007.2	7014.9	116577305.	455.	0.00006	-791.6019
10	546.5	223.2	769.8	17228.3	7036.9	117714198.	638.	0.00008	-719.0394
11	553.1	228.4	781.5	16993.4	7016.0	122039889.	450.	0.00006	-1053.3493
12	557.3	227.4	784.7	17063.8	6963.4	121535086.	202.	0.00003	-2117.2105
13	415.3	140.8	556.1	20225.5	7026.6	138208658.	1279.	0.00013	-298.0130
14	21.3	7.1	28.4	************	************	3281716.	124.	0.00015	0.0
15	55.0	6.8	61.7	************	************	31654766.	1345.	0.00028	0.0
16	17.4	3.8	21.2	************	************	10440827.	2490.	0.00048	0.0
17	12.8	2.5	15.3	************	************	5195068.	1863.	0.00078	0.0
18	10.6	2.1	12.7	************	************	5184252.	1460.	0.00052	0.0
19	10.3	2.0	12.3	************	************	5777412.	775.	0.00024	0.0
20	9.6	1.6	11.2	************	************	4545893.	96.	0.00004	0.0
21	9.7	0.5	10.2	************	************	2363194.	3.	0.00000	0.0
22	9.2	0.7	9.9	************	************	1341796.	4.	0.00001	0.0

MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

PAGE 14. 9

RUN NUMBER 14C
TEST DATE 7-15-82

PROCESSING DATE 7-21-82
TEST DURATION, SEC 140.00

H Y B R I D B E A R I N G D A T A
PUMP AND TURBINE END (PAGE 4)

	PUMP			TURBINE					
TIME SLICE NO	HS BRG CLEARANCE RADIAL IN	VISCOSITY PUMP BRG LB-HR/FT**2 * E10	CSUBP PUMP BRG BTU/ LB-R	HS BRG CLEARANCE RADIAL IN	VISCOSITY TURB BRG LB-HR/FT**2 * E10	CSUBP TURB BRG BTU/ LB-R	POISEUILLE RENOLDS NO	COUETTE RENOLDS NO	LAMBDA TURB NO
1	0.00207	0.41414	4.3323	0.00246	0.50857	2.9579	240040555.	1.	0.0000
2	0.00198	0.41443	4.3029	0.00246	0.51044	2.9544	244573676.	1.	0.0000
3	0.00215	0.38967	4.4677	0.00246	0.51064	2.9563	252398774.	1.	0.0000
4	0.00207	0.40472	4.3917	0.00246	0.50937	2.9615	262445833.	1186.	0.0000
5	0.00215	0.38788	4.7143	0.00244	0.50976	2.9630	269464793.	7066.	0.0003
6	0.00239	0.35279	5.8300	0.00242	0.50839	2.9726	269647280.	12960.	0.0005
7	0.00246	0.33521	6.5136	0.00238	0.50335	2.9875	266999691.	17753.	0.0007
8	0.00246	0.33562	6.2939	0.00236	0.50127	2.9948	263375612.	21115.	0.0008
9	0.00246	0.32318	6.7494	0.00244	0.48761	3.0292	297712161.	7176.	0.0003
10	0.00246	0.32178	6.7958	0.00246	0.48692	3.0317	307533549.	1.	0.0000
11	0.00246	0.31929	6.8367	0.00246	0.48829	3.0321	311685619.	1.	0.0000
12	0.00246	0.31727	6.9368	0.00246	0.48563	3.0419	312647120.	1.	0.0000
13	0.00245	0.20749	15.9704	0.00246	0.38667	3.3404	276466620.	1.	0.0000
14	0.00246	0.15215	2.7618	0.00245	0.15546	2.9867	6864308.	936.	0.0008
15	0.00245	0.11026	5.5871	0.00245	0.14414	6.4468	36222769.	719.	0.0002
16	0.00245	0.11276	5.1235	0.00246	0.14591	2.9180	2823382.	0.	0.0000
17	0.00245	0.11894	3.5822	0.00246	0.10882	5.3062	2589957.	4.	0.0000
18	0.00245	0.11464	4.0778	0.00246	0.12822	2.9052	458245.	1.	0.0000
19	0.00246	0.11162	4.6838	0.00246	0.10815	3.5491	232416.	0.	0.0000
20	0.00246	0.11170	3.9798	0.00246	0.09656	4.6333	306434.	0.	0.0000
21	0.00246	0.10435	2.9927	0.00246	0.08819	3.7478	1291348.	0.	0.0000
22	0.00246	0.11711	2.7453	0.00246	0.08620	3.6158	659710.	0.	0.0000

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MK48-I
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

RUN NUMBER 14C
TEST DATE 7-15-82

PROCESSING DATE 7-21-82
TEST DURATION, SEC 148.00

HYBRID BEARING DATA
TURBINE END (PAGE 1)

TIME SLICE NO	TURB BRG SUPPLY U/S PRESS (PSIA)	TURB BRG SUPPLY U/S TEMP (DEG R)	TURB BRG SUPPLY D/S ORIF PRESS (PSIA)	TURB BRG SUPPLY ORIF DP (PSID)	TURB BRG SUPPLY MANIF PRESS (PSIA)	TURB BRG DISCH PRESS (PSIA)	TURB BRG SUMP PRESS (PSIA)	-- TURBINE BRG -- DISCHARGE PRESS (PSIA)	-- TURBINE BRG -- LINE TEMP (DEG R)
1	2888.1	83.5	2776.3	146.5	2579.5	1485.7	1460.1	365.5	75.0
2	2965.1	84.4	2850.1	150.2	2647.5	1523.6	1498.2	374.4	76.1
3	3077.9	86.1	2960.0	154.9	2749.7	1580.5	1557.3	385.5	77.9
4	3215.6	88.4	3094.3	160.4	2876.6	1654.4	1632.3	398.3	79.8
5	3366.5	90.6	3239.1	168.7	3012.2	1726.6	1704.7	418.5	83.6
6	3469.3	92.8	3340.0	172.1	3108.6	1775.9	1752.6	437.5	86.1
7	3509.8	94.5	3393.3	170.7	3155.4	1794.9	1770.6	449.6	88.2
8	3563.1	95.9	3436.0	172.6	3209.2	1820.5	1796.2	457.0	89.7
9	3513.1	97.8	3390.5	169.4	3175.1	1804.3	1782.6	448.1	90.8
10	3549.6	98.6	3427.9	168.1	3213.5	1822.5	1802.6	447.5	91.4
11	3616.8	99.7	3495.2	167.8	3279.2	1858.6	1835.5	455.5	93.4
12	3622.0	100.6	3503.6	164.8	3287.8	1867.5	1847.4	453.7	94.3
13	2413.7	100.0	2388.7	94.3	2247.5	1252.5	1249.9	349.9	87.0
14	184.4	91.6	182.9	5.8	178.5	151.8	132.6	84.6	93.5
15	278.9	70.7	281.9	6.9	271.5	193.4	175.0	83.8	50.5
16	134.7	85.3	136.7	2.6	135.3	134.6	116.2	60.4	47.1
17	103.0	54.2	106.2	0.7	106.3	117.1	99.7	46.6	45.3
18	87.7	73.3	90.4	0.1	92.5	107.3	89.7	45.3	47.9
19	82.1	57.4	85.0	0.0	86.8	102.5	86.0	44.3	42.5
20	76.0	50.5	79.4	0.0	80.3	96.2	79.6	42.2	42.7
21	51.0	47.2	54.3	0.0	54.7	64.4	50.8	39.7	43.5
22	46.6	46.2	49.0	0.0	49.2	59.5	47.1	34.3	42.3

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MK48-F
LIQUID HYDROGEN TURBOPUMP ASSEMBLY

MBER 14C
ATE 7-15-82

PROCESSING DATE 7-21-82
TEST DURATION, SEC 148.00

HYBRID BEARING DATA
TURBINE END (PAGE 2)

MF ICE NO	SHAFT SPEED (RPM)	TURBINE CARTRIDGE SPEED (RPM)	TURBINE H/S BRG FLOW (LB/SEC)	LH2 DENSITY AT ORIF (PCF)	TURB BRG SUPPLY MANIF PRESS (PSIA)	TURB BRG DISCH PRESS (PSIA)	TURB BRG SUMP PRESS (PSIA)	HYDROSTATIC BEARING DELTA PRESS (PSID)
1	76875.	1.	0.3980	4.307	2579.5	1485.7	1460.1	1119.40
2	77908.	1.	0.4033	4.315	2647.5	1523.6	1498.2	1149.38
3	79397.	1.	0.4097	4.317	2749.7	1580.5	1557.3	1192.41
4	81168.	1323.	0.4168	4.314	2876.6	1654.4	1632.3	1244.31
5	[illegible]	7974	0.4277	4.319	3012.2	1726.6	1704.7	1307.49
6	84955.	14878.	0.4314	4.309	3108.6	1775.9	1752.6	1355.94
7	85052.	20687.	0.4285	4.286	3155.4	1794.8	1770.6	1384.72
8	85676.	24957.	0.4302	4.276	3209.2	1820.5	1796.2	1413.0[illegible]
9	85338.	8158.	0.4235	4.217	3175.1	1804.3	1782.6	1392.48
10	85842.	1.	0.4216	4.213	3213.5	1822.5	1802.6	1410.86
11	86572.	1.	0.4213	4.214	3279.2	1858.6	1839.5	1439.70
12	86687.	1.	0.4167	4.197	3287.8	1867.5	1849.4	1438.47
13	72294.	1.	0.2950	3.680	2247.5	1252.5	1249.9	997.64
14	52453.	4814.	0.0748	0.420	170.5	151.8	132.6	45.87
15	19247.	1594.	0.0426	1.202	271.5	193.4	175.0	96.57
16	9125.	1.	0.0146	0.326	135.3	134.6	116.2	19.03
17	5019.	11.	0.0091	0.509	107.3	117.1	99.7	6.58
18	2892.	6.	0.0027	0.248	92.5	107.3	89.7	2.81
19	1536.	1.	0.0	0.378	86.8	102.5	86.0	0.79
20	1.	1.	0.0	0.379	80.3	96.2	79.6	0.75
21	1.	1.	0.0	0.25[illegible]	54.7	64.4	50.8	3.87
22	1.	1.	0.0	0.231	49.2	59.5	47.1	2.05

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