NASA CR 54816
AGC 8800-23

DEVELOPMENT OF LIQUID OXYGEN COOLED 110MM ROLLER AND TANDEM BALL BEARINGS AT UP TO .5 x 10^6 DN VALUES FOR THE OXIDIZER TURBOPUMP OF THE M-1 ENGINE

By

M. W. Young
L. F. Kirby

Prepared for

National Aeronautics and Space Administration

Contract NAS 3-2555

AEROJET GENERAL TIRE GENERAL

AEROJET-GENERAL CORPORATION

SACRAMENTO, CALIFORNIA

Requests for copies of this report should be referred to:

National Aeronautics and Space Administration
Office of Scientific and Technical Information
Attention: AFSS-A
Washington, D. C. 20546

NASA CR-54816
AGC 8800-23

TECHNOLOGY REPORT

DEVELOPMENT OF LIQUID OXYGEN COOLED 110MM ROLLER AND TANDEM BALL BEARINGS AT UP TO .5 x 10^6 DN VALUES FOR THE OXIDIZER TURBOPUMP OF THE M-1 ENGINE

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

March 11, 1966

CONTRACT NAS 3-2555

Prepared by:

AEROJET-GENERAL CORPORATION
LIQUID ROCKET OPERATIONS
SACRAMENTO, CALIFORNIA

AUTHORS: M. W. Young
L. F. Kirby

APPROVED: W. E. Campbell
Manager
M-1 Turbopump Project

Technical Management:

NASA LEWIS RESEARCH CENTER
CLEVELAND, OHIO

TECHNICAL MANAGEMENT: K. L. Baskin
M. M. Bailey

APPROVED: W. F. Dankhoff
M-1 Project Manager

19631

ABSTRACT

A development program for the purpose of evaluating the suitability of the bearing package designed for the M-1 liquid oxygen turbopump was completed. The test results indicate that the bearing performance is adequate as compared with that predicted during the design phase. The 110 mm roller and tandem ball bearings were demonstrated at $.5 \times 10^6$ DN values, radial loads of 15,000 lb and thrust loads up to 70,000 lb (twice the rated load). Liquid oxygen and liquid nitrogen were used as coolants; bearing materials were 440C stainless steel with armalon cages.

author

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. SUMMARY

This report describes the activity and results of the program to develop liquid oxygen cooled bearings for use in the oxidizer turbopump of the M-1 Engine. The objectives of this development program were to obtain bearing operational information and to qualify the bearings for use in the turbopump.

The basic bearing configuration selected for use in the turbopump consisted of a single 110 mm roller bearing on the output (pump) end, a single 105 mm roller bearing on the input (turbine) end, and a tandem set of two 110 mm ball bearings mounted between those on the common shaft. The shaft and housing were sized to provide radial interference fits on the roller bearings and ball bearing inner races, and clearance fits on the ball bearing outer races. The coolant supply system was basically a "total immersion system", but coolant jets were provided to assure circulation through the bearings.

Design operating requirements were as follows:

		Output Roller	Input Roller	Tandem Ball
Load	lb	15,000	7,000	35,000
Speed	rpm	3,720	3,720	3,720
Acceleration	rpm/sec	7,200	7,200	7,200

Five basic test setups, ranging in complexity from a turbine-driven, single-bearing tester to the complete turbopump system were used during the program. These testers provided the capability to simulate turbopump operation on multiple combinations of ball and roller bearings under controlled conditions of load, acceleration, speed, and coolant properties.

Early testing of commercially-available thrust bearings yielded valuable operational information such as pre-test cooling requirements, load and speed control relationships, and tester capability. The results of the testing also indicated that tests of a large number of bearing configurations were unnecessary in selecting a bearing design suitable for the intended loads, speed, and acceleration. The test program was modified to concentrate effort upon the qualification of tandem thrust bearings manufactured by the New Departure Corp. and roller bearings produced by SKF Industries, Inc. Qualification testing provided bearing life information at turbopump operating conditions. Load sharing tests performed with the tandem thrust bearings received special attention because good load sharing would contribute to safe turbopump operation at off-design conditions. A special qualification test series was conducted using liquid nitrogen as the bearing coolant because early turbopump testing would be conducted using liquid nitrogen to simulate a propellant.

Performance of all preferred-configuration bearings was excellent, with life in excess of 5000 sec at design radial and axial loads in liquid oxygen and of at least 200 sec at or near 100% axial overload at DN values of $.5 \times 10^6$. Performance using liquid nitrogen as a coolant was equally satisfactory. The excellent post-test condition of the bearings used in the first turbopump test series demonstrated that component test results are directly applicable to the turbopump.

II. INTRODUCTION

In the M-1 liquid oxygen turbopump, power is transmitted through a single shaft connecting the pump impeller to the turbine rotor. Therefore, the power transmission components are located between the liquid oxygen pump and the hot gas turbine. The extreme complexity of seals, heaters, and auxiliary pumping systems required for conventional oil lubrication made it desirable that the bearings be cooled with liquid oxygen. The requirement that the shaft system be rigid enough to prevent interference between rotating and static parts under load dictated that the bearing minimum size should be approximately 110 mm bore and that axially rigid ball bearings be used to support end thrust.

The development of the bearing system which was selected as indicated is the subject of this report, which describes the effort and results obtained during the program conducted by Aerojet-General Corporation under Contract NAS3-2555 to the National Aeronautics and Space Administration.

III. <u>BEARING DEVELOPMENT PROGRAM</u>

A. DEVELOPMENT PROGRAM OBJECTIVES

The bearing development program was planned to yield operational information concerning liquid oxygen cooled bearings such as the required coolant flow rate and pressure, cooling rate (chilldown time), malfunction behavior (temperature rise, torque increase, vibration level), and purging or drying requirements; and to survey the performance (load-life relationship) of a large number of bearings produced by different manufacturers. Results of very successful early testing indicated that the survey testing was unnecessary, and the program was modified to concentrate effort upon qualification of the preferred configuration thrust bearing (P/N 281642/700797), turbine end roller bearing (P/N 281643), and pump end roller bearing (P/N 281644) for use in the turbopump. The qualification test program was planned to provide bearing life information at varying conditions of load, load direction, load sharing, load application rate, speed, acceleration, coolant flow rate, coolant pressure, coolant properties (liquid oxygen and liquid nitrogen), and initial (pre-test) temperature.

B. BEARING CONFIGURATION

1. <u>Arrangement of Bearings in the Turbopump</u>

a. Assembly Arrangement

Bearings were arranged as shown in Figures 1 and 2 on a common shaft with a 110 mm bore x 170 mm O.D. x 28 mm long roller bearing on the pump (output) end, a 105 mm bore x 160 mm O.D. x 26 mm long roller bearing on the turbine (input) end, and with the tandem set of two 110 mm bore x 170 mm O.D. x 28 mm long ball thrust bearings located between the roller bearings, adjacent to the pump end roller.

The bearings/shaft assembly was encased in a common (one-piece) housing to provide positive control of relative radial position and alignment of the roller bearings.

b. Mounting and Fits

The bearings were mounted on the shaft with the required spacers and jet rings and clamped in place by a lock nut.

Bearing fits (inner race to shaft and outer race to housing) were the same for all manufacturers' bearings. Fits between shafts or housings and prototype bearings were as follows:

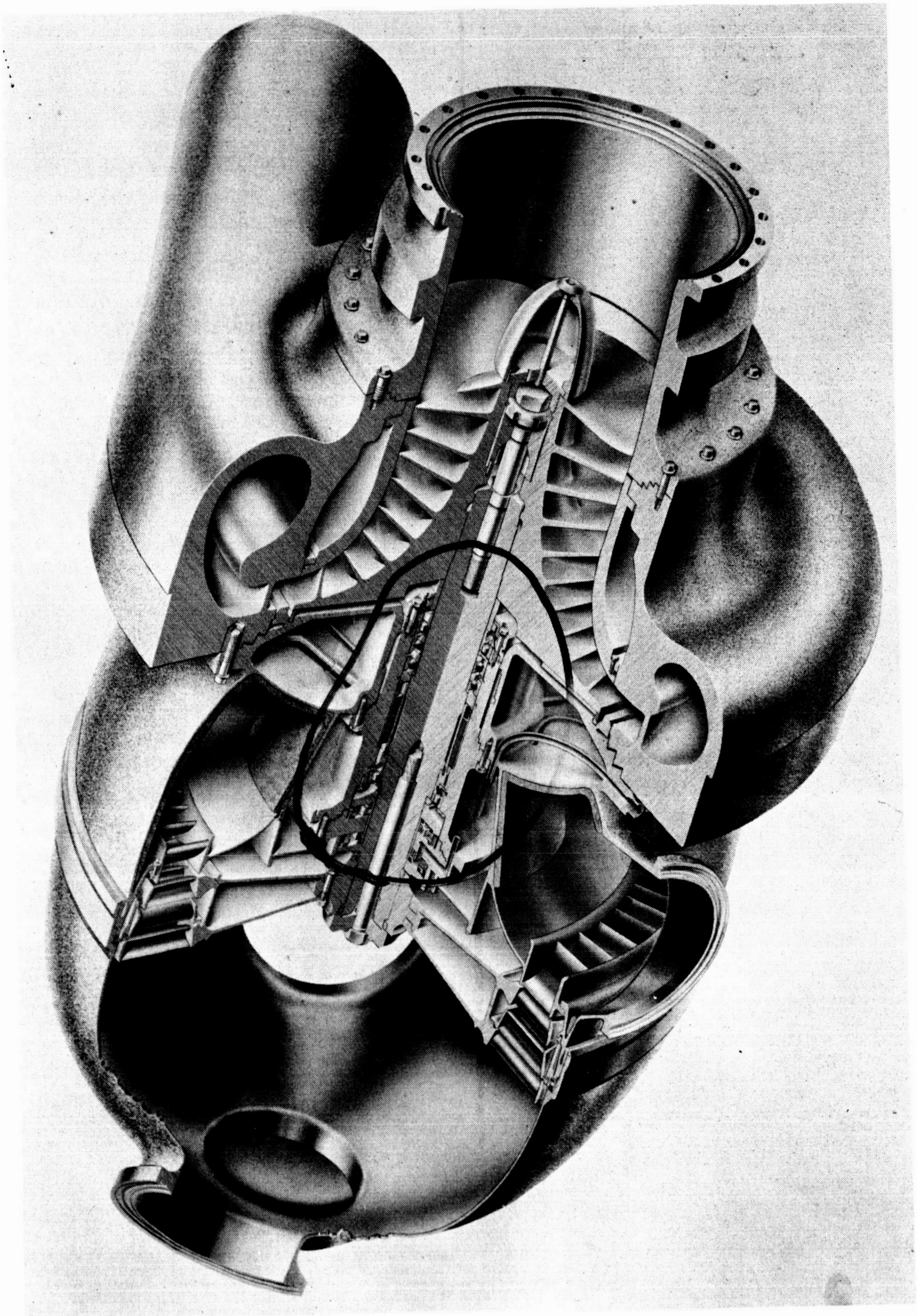

Figure 1

Oxidizer Turbopump Assembly

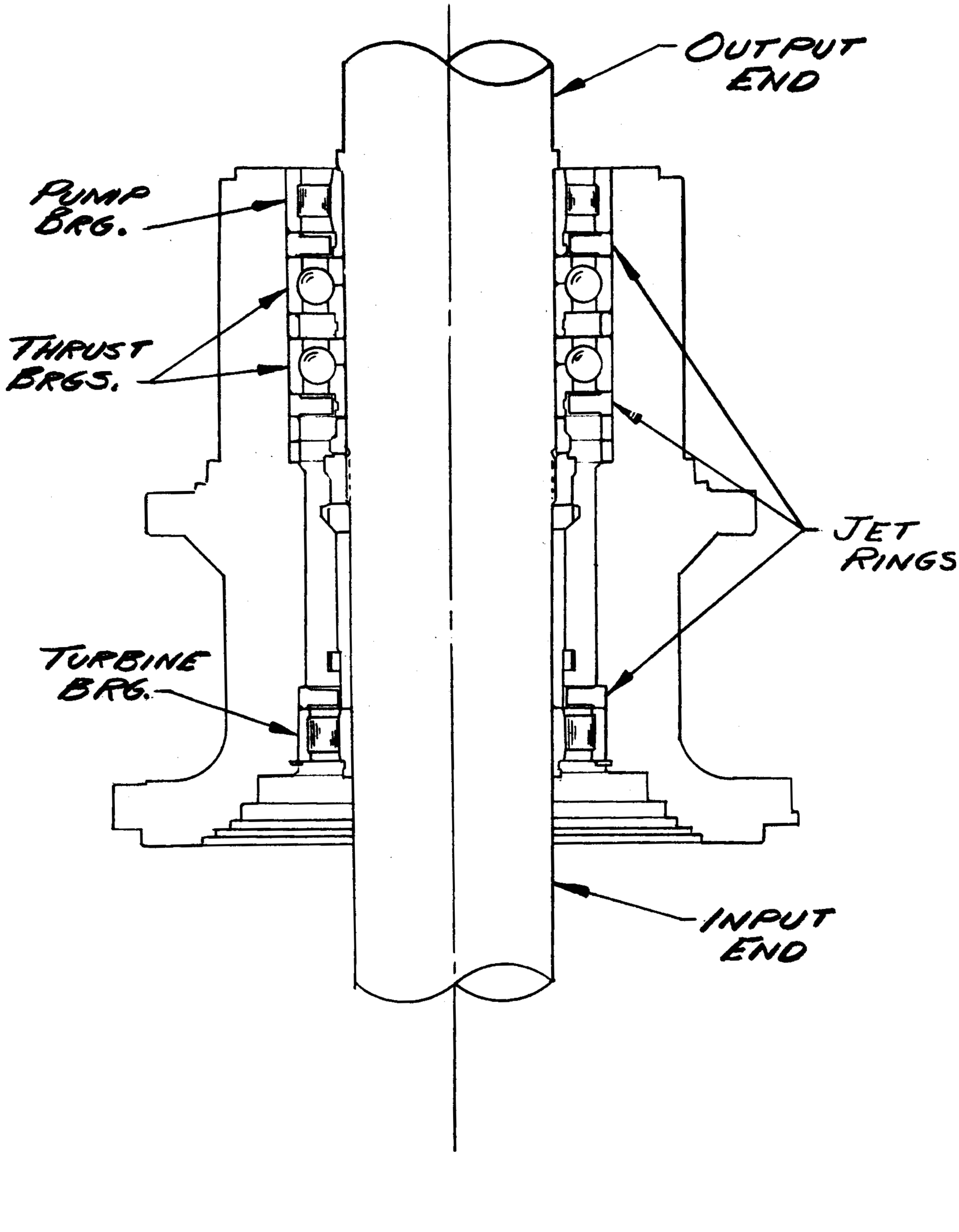

Figure 2

Turbopump Power Transmission

Type of Bearing	Diametral Fit Inner Race to Shaft (in.) Ambient Temperature	Diametral Fit Inner Race to Shaft (in.) Operating Temperature(-287°F)	Diametral Fit Outer Race to Housing (in.) Ambient Temperature	Diametral Fit Outer Race to Housing (in.) Operating Temperature(-287°F)
Pump Roller P/N 281644	0.0017/0.0023 Tight	0.0004/0.0010 Tight	0.0003/0.0012 Loose	0.0015/0.0024 Tight
Turbine Roller P/N 281643	0.0017/0.0023 Tight	0.0004/0.0010 Tight	0.0003/0.0012 Loose	0.0013/0.0022 Tight
Thrust Bearing P/N 281642	0.0012/0.0018 Tight	0.0001 Loose/ 0.0005 Tight	0.0131/0.0146 Loose	0.0104/0.0119 Loose

Assembly of the bearings was facilitated by heating the bearings to 300°F/350°F before installation to overcome the interference fit between the inner race and shaft.

c. Coolant System

Coolant was supplied to the bearings through jet rings which direct the coolant directly on the rolling elements. The jet ring passage has an annular distribution channel with axial exit, cylindrical spray nozzles.

The jet rings were arranged in the turbopump (Figure 2) with one ring between the pump end roller bearing and the adjacent thrust bearing supplying coolant through five 0.050-in. diameter holes to the roller bearing and through fifteen 0.050-in. diameter holes to the thrust bearing; one jet ring supplied the lower thrust bearing through fifteen 0.050-in. diameter holes; and one jet ring with five 0.050-in. diameter holes supplied coolant to the turbine end roller bearing.

The jet rings were designed to supply coolant to dissipate the heat generated at design radial and thrust loads at the approximate rates of 1.4 gpm per bearing for the radial bearings and 5.7 gpm per bearing for the thrust bearings(1).

2. Operating Conditions

a. Thrust Bearings

Tandem thrust bearings were manufactured by two vendors: the New Departure Corp. (P/N 281642 and 700797) and Industrial Tectonics, Inc. (P/N 288280). Thrust bearings P/N 281642 and 700797 are identical except for

---

(1) Dubief, J., Heat Generation in Annular Contact Ball Bearings Under Axial Load, Report RMR 0075, Aerojet-General, 16 January 1963.

being matched for load sharing in opposite directions relative to their orientation in the turbopump. Single thrust bearings were manufactured by the same vendors: the New Departure Corp. (P/N EX31000C) and Industrial Tectonics, Inc. (P/N 288140).

The operating conditions for the tandem bearings were as follows:

Operating Condition	P/N 281642 and 700797	P/N 288280
Thrust Load (Sharing Direction), lb	35,000	40,000
Thrust Load (Reverse Direction), lb	8,000	5,000
Overload (Sharing Direction), lb	39,000	44,000
Overload (Reverse Direction), lb	9,000	5,500
Speed, rpm	3,720	3,720
Overspeed, rpm	4,000	4,000
Acceleration Rate, rpm/sec	7,200	7,200
Coolant Flow Rate, gpm/Bearing	5.72	5.72
Coolant Pressure, psig	450	450
Coolant Temperature, LN_2, °F	-320	-320
Coolant Temperature, LO_2, °F	-297	-297

b. Radial Bearings

Radial load roller bearings were manufactured by the SKF Industries, Inc., with the following operational requirements:

Operating Condition	Pump Bearing P/N 281644	Turbine Bearing P/N 281643
Radial Load, lb	15,000	7,000
Radial Overload, lb	16,500	8,000
Speed, rpm	3,720	3,720
Overspeed, rpm	4,000	4,000
Acceleration Rate, rpm/sec	7,200	7,200

Operating Condition	Pump Bearing P/N 281644	Turbine Bearing P/N 281643
Coolant Flow Rate, gpm	1.394	1.394
Coolant Pressure, psig	450	450
Coolant Temperature, LO_2, °F	-297	-297
Coolant Temperature, LN_2, °F	-320	-320

3. Design Data

a. Thrust Bearings

(1) New Departure Corp. (ND)

Two separate bearings were manufactured by New Departure for the bearing evaluation program: a single thrust bearing and a tandem thrust bearing set.

The single bearing (P/N EX31000C) had a nonseparable outer race, ball, and cage assembly with a split inner race without puller grooves. The tandem bearing (P/N 281642/700797) was made up of two bearings matched for optimum load sharing. The bearings were completely separable with puller grooves on the inner races.

Both bearings were made with the same materials, AISI 440C Stainless Steel races and balls and Armalon 405C-116 cages. Design details of these bearings are as follows:

	P/N 281642/700797	P/N EX31000C
Type	Duplex Tandem	Single
Size	110 mm x 170 mm x 28 mm	110 mm x 170 mm x 28 mm
No. of Balls	19	18
Size of Balls	3/4 in.	25/32 in.
Class	ABEC5	ABEC5
Contact Angle	20°	25°
Race Curvature	52% Inner, 52% Outer	52% Inner, 56% Outer

	P/N 281642/700797	P/N EX31000C
Radial Clearance at Ambient Temperature	0.0038/0.0042	0.0115/0.0119
End Play	0.017/0.023	0.049/0.053
Cage Design	One Piece, Reinforced with Aluminum Side Plates	One Piece, Reinforced with Aluminum Side Plates

(2) Industrial Tectonics, Inc. (ITI)

Two separate bearings were made for the bearing evaluation program by ITI, a single thrust bearing (P/N 288140) and a tandem thrust bearing (P/N 288280). The bearings were similar in design and made of the same material, AISI 440C Stainless Steel races and balls and Armalon 405C-116 cages. The cage design incorporated a controlled ball drop. Design details of these bearings are as follows:

	P/N 288280	P/N 288140
Type	Duplex Tandem	Single
Size	110 mm x 170 mm x 28 mm	110 mm x 170 mm x 28 mm
No. of Balls	20	19
Size of Balls	23/32	3/4
Class	ABEC7	ABEC7
Contact Angle	30°	27.5°
Race Curvature	53% Inner, 52% Outer	52% Inner, 54% Outer
Radial Clearance at Ambient Temperature	0.0063/0.0069	0.0083/0.0087
End Play	0.020/0.025	0.0223/0.0255
Cage Design	One Piece, Reinforced with Aluminum Side Plates	One Piece, Reinforced with Aluminum Side Plates

b. Radial Bearings

Pump and the turbine-end radial bearings were manufactured by SKF Industries, Inc. These radial bearings also used 440C race and roller material and Armalon 405C-116 cages.

Design details of these bearings are as follows:

	P/N 281643	P/N 281644
Size	105 mm x 160 mm x 26 mm	110 mm x 170 mm x 28 mm
No. of Rollers	19	19
Size of Rollers	15 mm dia., 17 mm long	16 mm dia., 16 mm long
Roller Configuration	Crowned	Crowned
Class	ABEC 5	ABEC 5
Diametral Clearance at Ambient Temperature	0.0029 to 0.0033	0.0030 to 0.0034
Cage Design	One Piece, Reinforced with Aluminum Side Plates	One Piece, Reinforced with Aluminum Side Plates

4. Operating Stresses (Prototype Bearings)

a. Thrust Bearings

An analysis was made to determine the contact, hoop, and radial stresses at ambient and operating temperatures for the two-bearing tandem stack (P/N 281642); the total shared load was assumed to be 33,000 lb. This study was made under two loading conditions: 50%/50% load sharing and 60%/40% load sharing. The results are shown in Table I.

The dynamic contact angles of 34.1 degrees on the inner race and 33.8 degrees on the outer race for the prototype bearing at 4000 rpm and 16,500-lb load results in the contact ellipse being confined well within the design shoulder height.

b. Roller Bearings

An analysis of hoop and compressive stresses was completed for roller bearings P/N 281644 (pump end) and P/N 281643 (turbine end) at ambient temperature with no load at operating temperature and design load. Stresses were calculated using maximum interference fits. The results were as follows:

	P/N 281644		P/N 281643	
	Operating Temperature		Operating Temperature	
	Ambient	-287°F	Ambient	-287°F
Radial Load, lb	0	17,680	0	9,970
Inner Race Hoop Stress, psi	13,500	500	16,800	1,240
Inner Race Radial Stress, psi	*1520	*144	*1880	*139
Outer Race Tangential Stress, psi	0	6,070	0	3,880
Outer Race Radial Stress, psi	0	*610	0	*810
Inner Race Contact Stress, psi	0	264,000	0	204,000
Outer Race Contact Stress, psi	0	235,000	0	182,000

*Compressive stress

TABLE I

CALCULATED STRESSES FOR M-1 LIQUID OXYGEN THRUST BEARING P/N 281642

Temperature (°F)	Single Row Load (lb)	Speed (rpm)	Free Cont. Angle (Deg)	Mounted Cont. Angle (Deg)	Dynamic Cont. Angle (Degrees) On Inner Race	Dynamic Cont. Angle (Degrees) On Outer Race	Radial Interference (in.)	Max. Comp. Stress (Hertz) (psi)	Tangential Stress (Hoop) Inner Race (psi)	Radial Stress Inner Race (psi)	Clamping Load on Inner Race (lb)	Load Sharing
68	0	0	23	20.75	--	--	0.0011	--	6,750	*1,170	10,492	
-297	0	0	23	22.5	--	--	0.0002	--	1,230	*213	58,682	
-297	16,500	4,000	23	22.1	34.10	33.8	0.0002	347,690	1,230	*213	58,682	50%/50%
-297	20,000	4,000	23	22.1	34.10	33.8	0.0002	410,000	1,230	*213	58,682	60%/40%

*Compressive Stress

C. TEST PROGRAM

1. Bearing Testers

a. Turbine Driven Testers

(1) Single Bearing Evaluation

The turbine-driven, single-bearing test head shown schematically in Figures 3 and 4 was designed to test two single thrust bearings, arranged in opposed load directions, at total loads up to 20,000 lb and shaft speeds of up to 6000 rpm. The bearings were mounted on a direct-drive shaft encased in an axially floating housing incorporating an internal hydraulic load-actuation system. The load was applied directly to the outboard bearing, through the hydraulic actuation system, and appeared in the inboard bearing as a resistive reaction load. Coolant back pressure caused by scavenge line pressure drop acting upon the floating test housing resulted in unequal loads in the two bearings, which was evident when the "inboard" and "outboard" loads were compared from the test results.

The drive unit consisted of an independently mounted, modified Titan turbine using gaseous nitrogen as the drive gas.

(2) Acceleration Evaluation

The acceleration performance tester shown in Figures 5 and 6 was designed to test one ball thrust bearing and one roller bearing at acceleration rates up to 25,000 rpm/sec at partial load. The bearings were mounted on a directly driven shaft encased in a common (one-piece) housing. Both axial and radial loads were applied through external hydraulic load actuators.

The drive unit was the same as that used for the single bearing tester.

b. Motor Driven Tester

The motor driven bearing tester (Figures 7 and 8) was a versatile, multiple bearing test unit adaptable to several combinations of ball and roller bearings. Sets of test bearings were installed in each of two cartridge or carrier assemblies. The two cartridges were coupled together with a splined shaft and installed in the main housing with an additional slave roller bearing on the input end of the shaft to isolate motor side loads. Both axial and radial loads were applied through integral hydraulic load actuators.

Although the tester was adaptable to many combinations of test bearings, the only two used in the M-1 oxidizer bearing test program were the tandem thrust bearing assembly (Figure 9) and the roller bearing assembly (Figure 10).

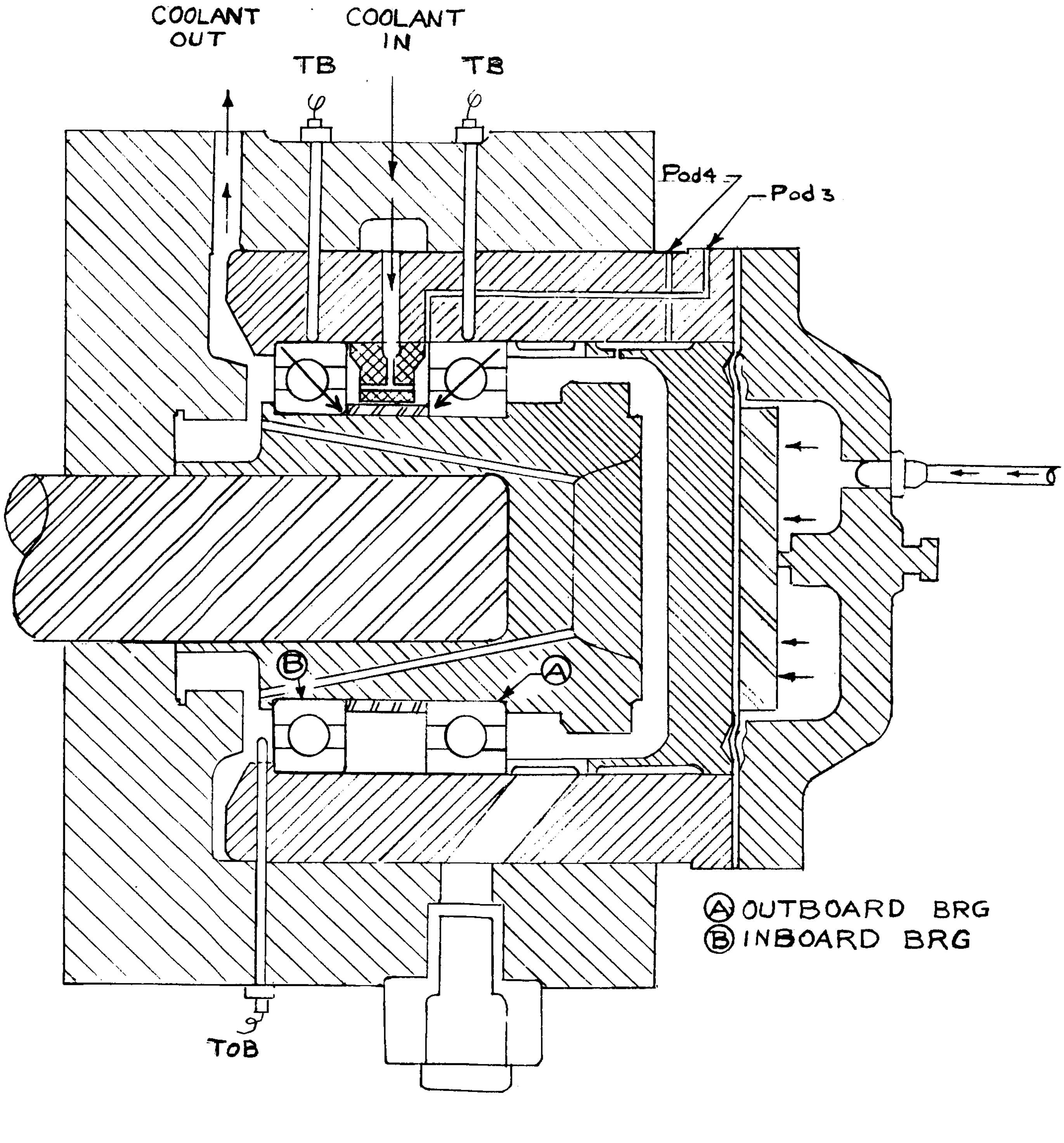

Figure 3

Test Head, Single Thrust Bearing

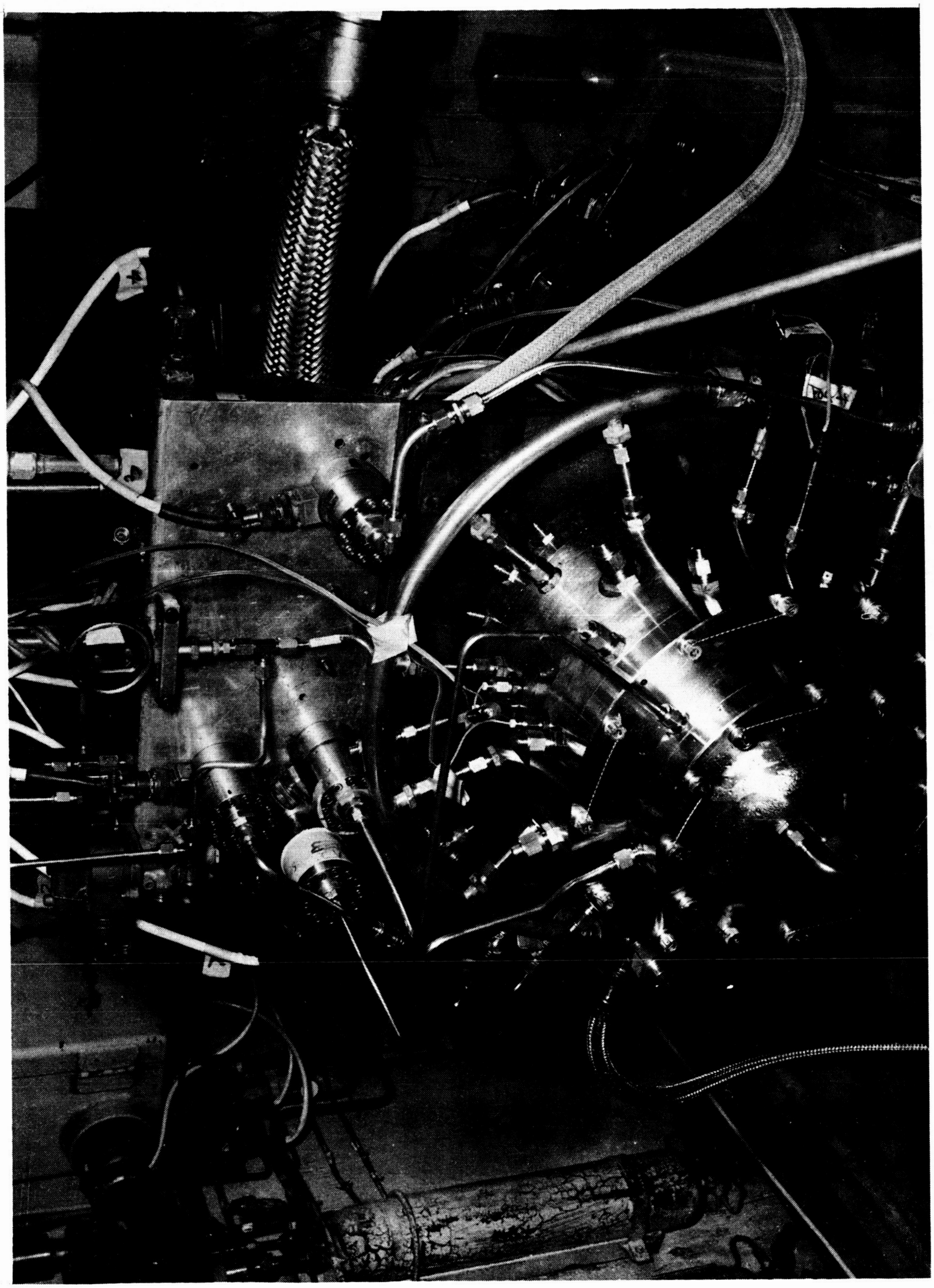

Figure 4

Test Stand, Single Thrust Bearing Tester

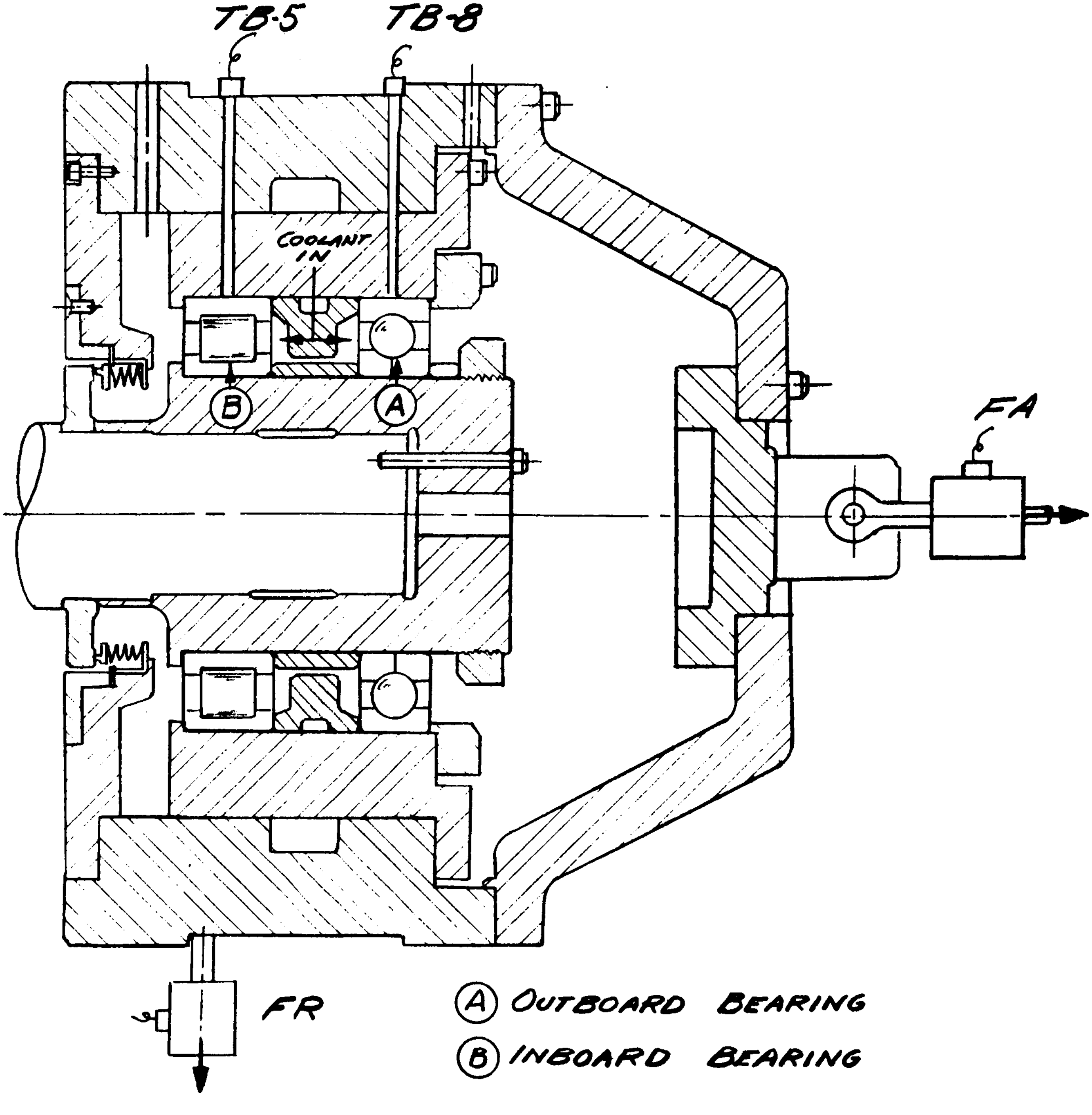

Figure 5

Test Head, Acceleration Tester

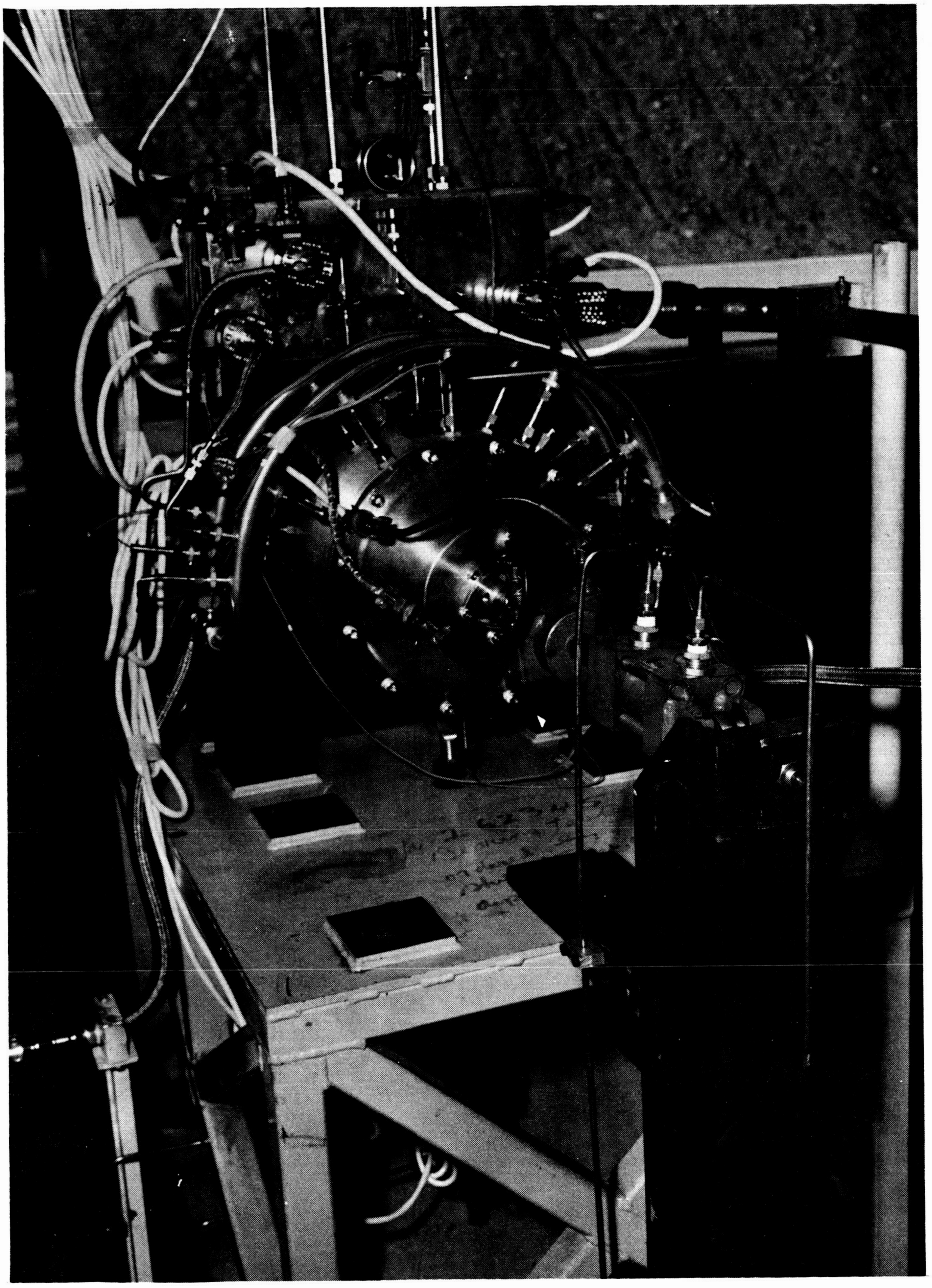

Figure 6

Test Stand, Acceleration Tester

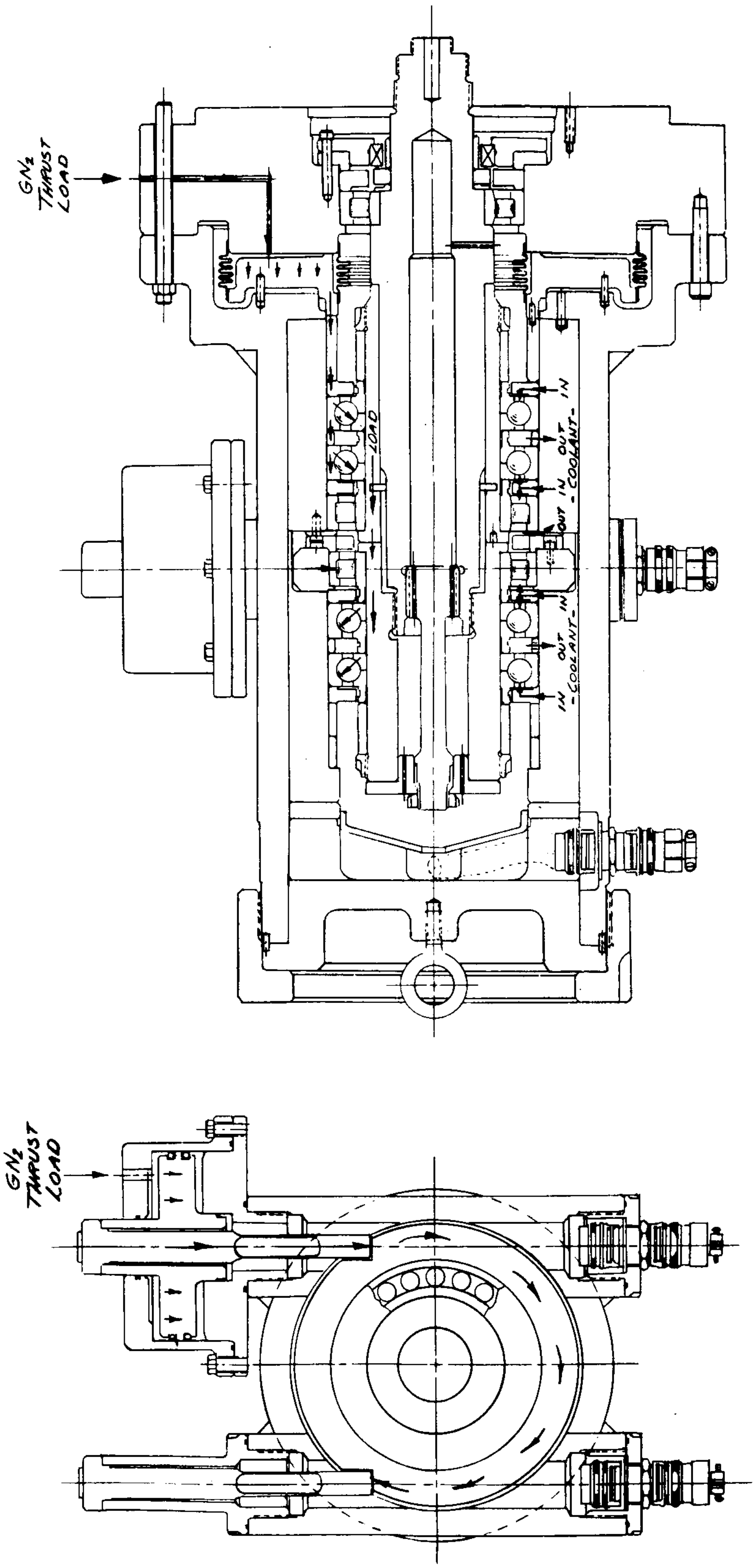

Figure 7

Test Head, Motor Driven Bearing Tester

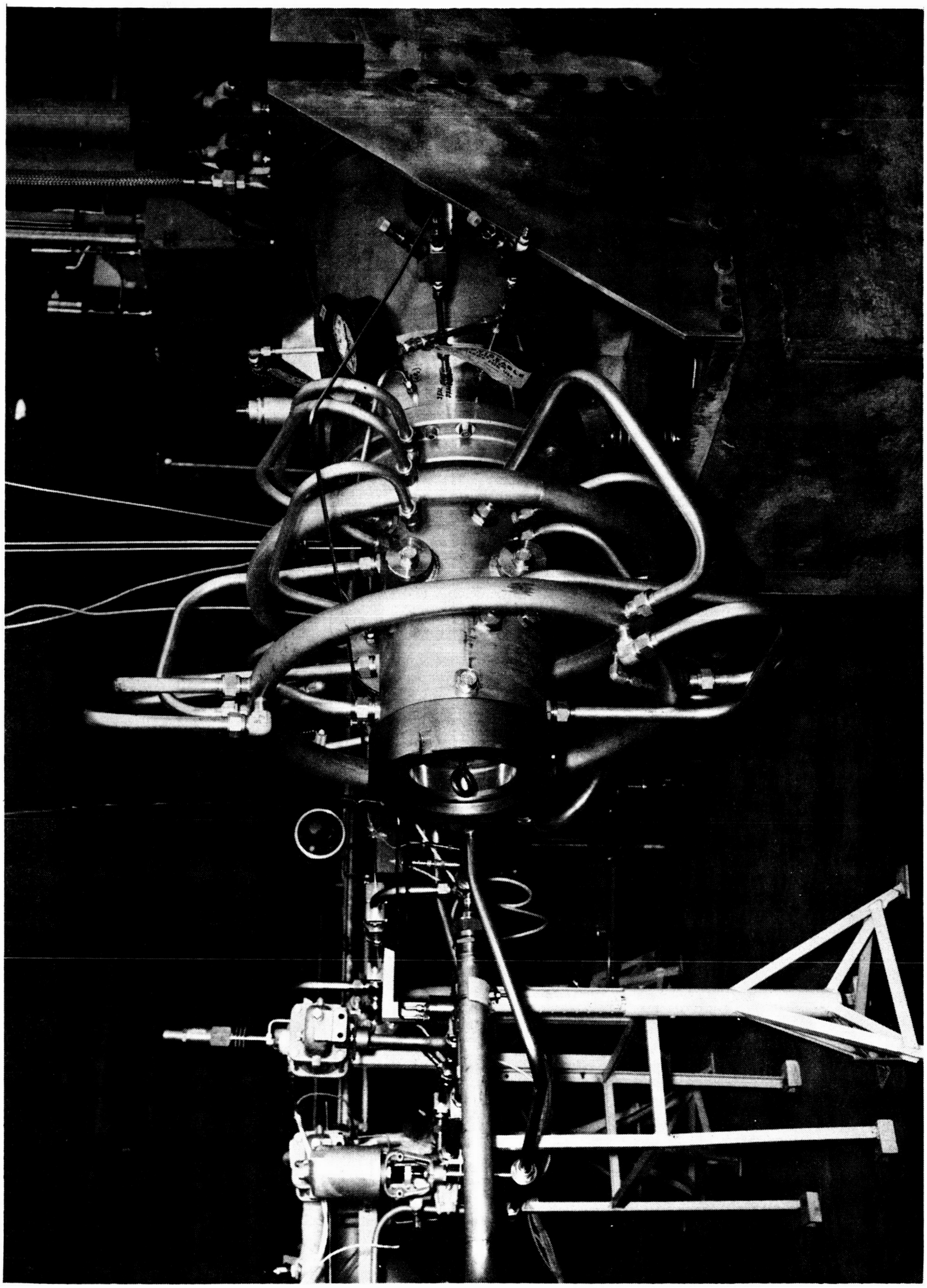

Figure 8

Motor Driven Tester

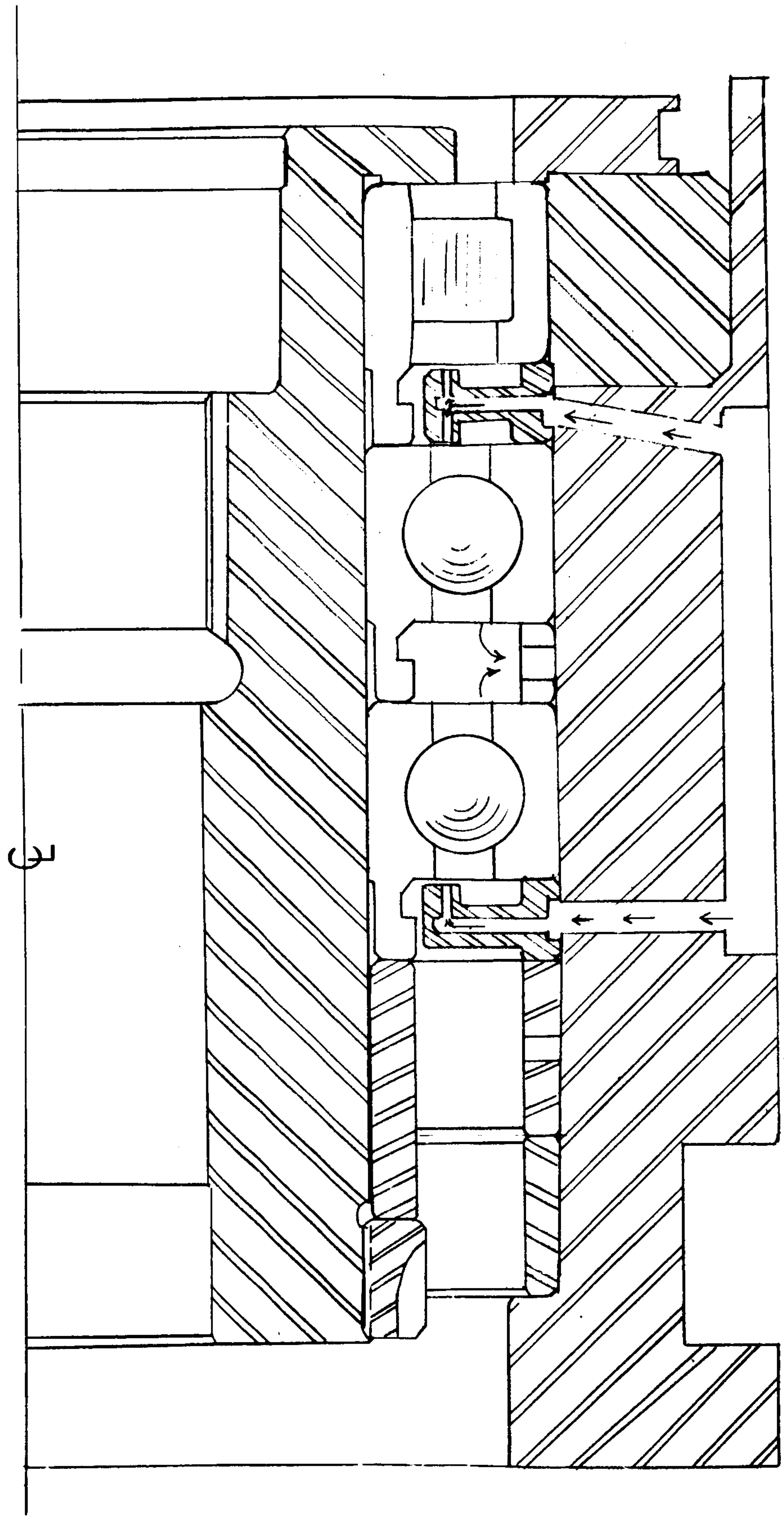

Figure 9

Tandem Bearing Test Head

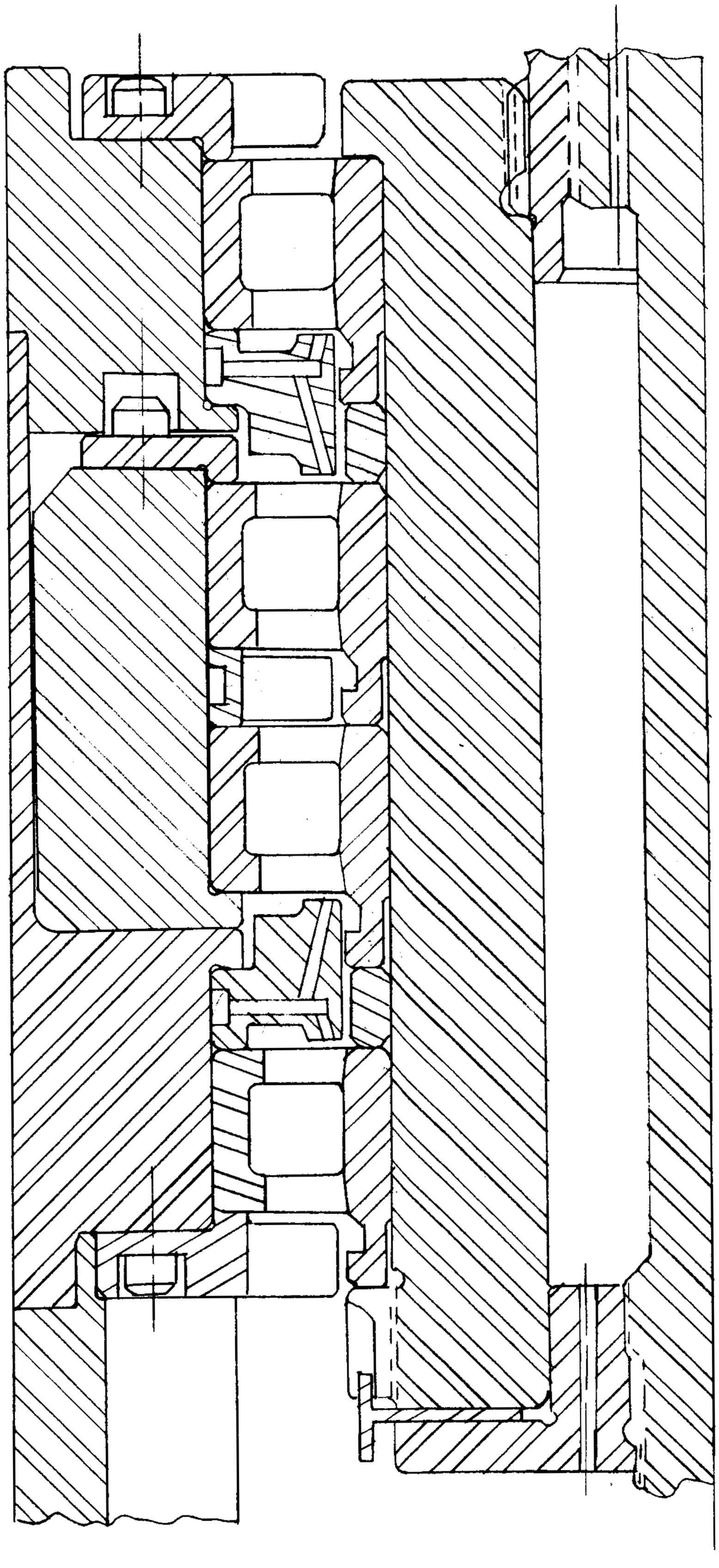

Figure 10

Roller Bearing Test Head

The tester was driven by a 440-volt, three-phase induction motor developing 350 hp at 20,000 rpm. A variable-frequency power supply allowed accurate speed control over a speed range from 1000 to 20,000 rpm. Available motor torque varied linearly from 20 lb-ft at 1000 rpm to 80 lb-ft at 20,000 rpm. Maximum acceleration capability varied from 750 rpm/sec at design bearing loads to 2000 rpm/sec at no load.

c. Power Transmission Tester

The power transmission (PTA) tester shown on Figures 11 and 12 consisted of two turbopump power transmissions (Figure 13) coupled together at the shaft output ends. Axial loading was accomplished by a system of actuators that forced the bearing housings toward each other to simulate turbopump loading in the downward (toward the turbine) direction and forced the housings apart to simulate upward loading. Radial load was applied by an actuator that shifted the bearing housing centers from their initial aligned position. Provisions for simulating turbine heating effects were incorporated into the unit.

The tester was driven by a 500-hp, 4000-rpm steam turbine through a right-angle gearbox, a fly wheel, and a planetary gear speed increaser. A retarder brake assembly, used in conjunction with the planetary gear system, allowed accurate acceleration control up to 32,000 rpm/sec at no load.

2. <u>Operational Considerations</u>

a. Controls

(1) Speed and Acceleration

(a) Turbine Driven Tester

The speed of the turbine driven testers was controlled by manually regulating the turbine inlet pressure based upon a digital readout tachometer. The slow response characteristics of the manual system prohibited rapid application or removal of the load if good speed control was to be maintained. Therefore, transient load studies were not practical without extensive control modifications, and testing with this tester was limited to steady load tests and no-load acceleration tests.

Acceleration was controlled by pre-setting turbine inlet pressures upstream of a fast-actuating valve. Pre-set pressure levels were determined on a "trial and error" basis.

Deceleration was normally accomplished by manual-remote closure of the turbine gas flow control valve, which allowed the tester to coast to a stop. An automatic overspeed protection system, which vented turbine driven gas to atmosphere in the event of an overspeed signal, was provided.

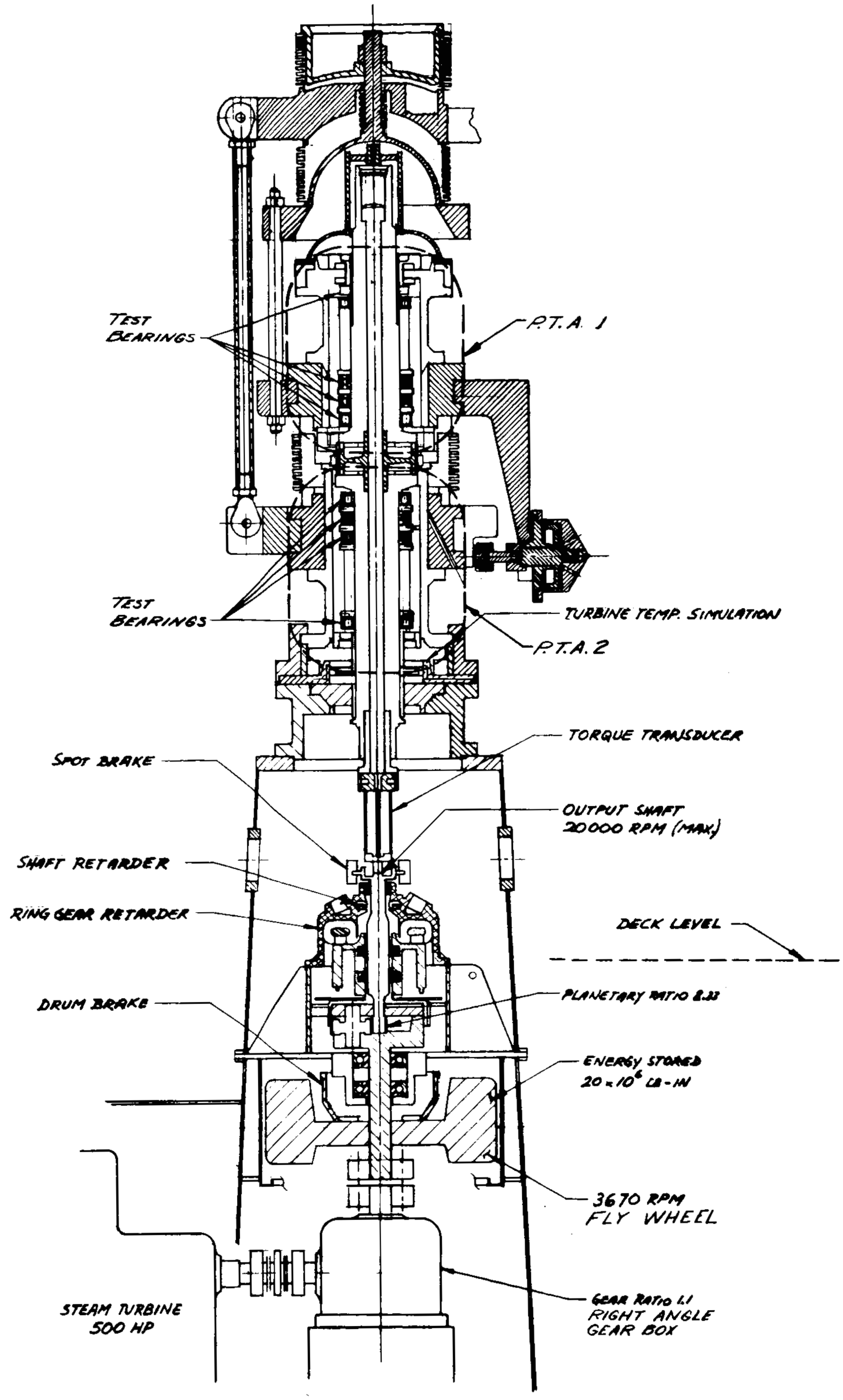

Figure 11

Power Transmission Tester

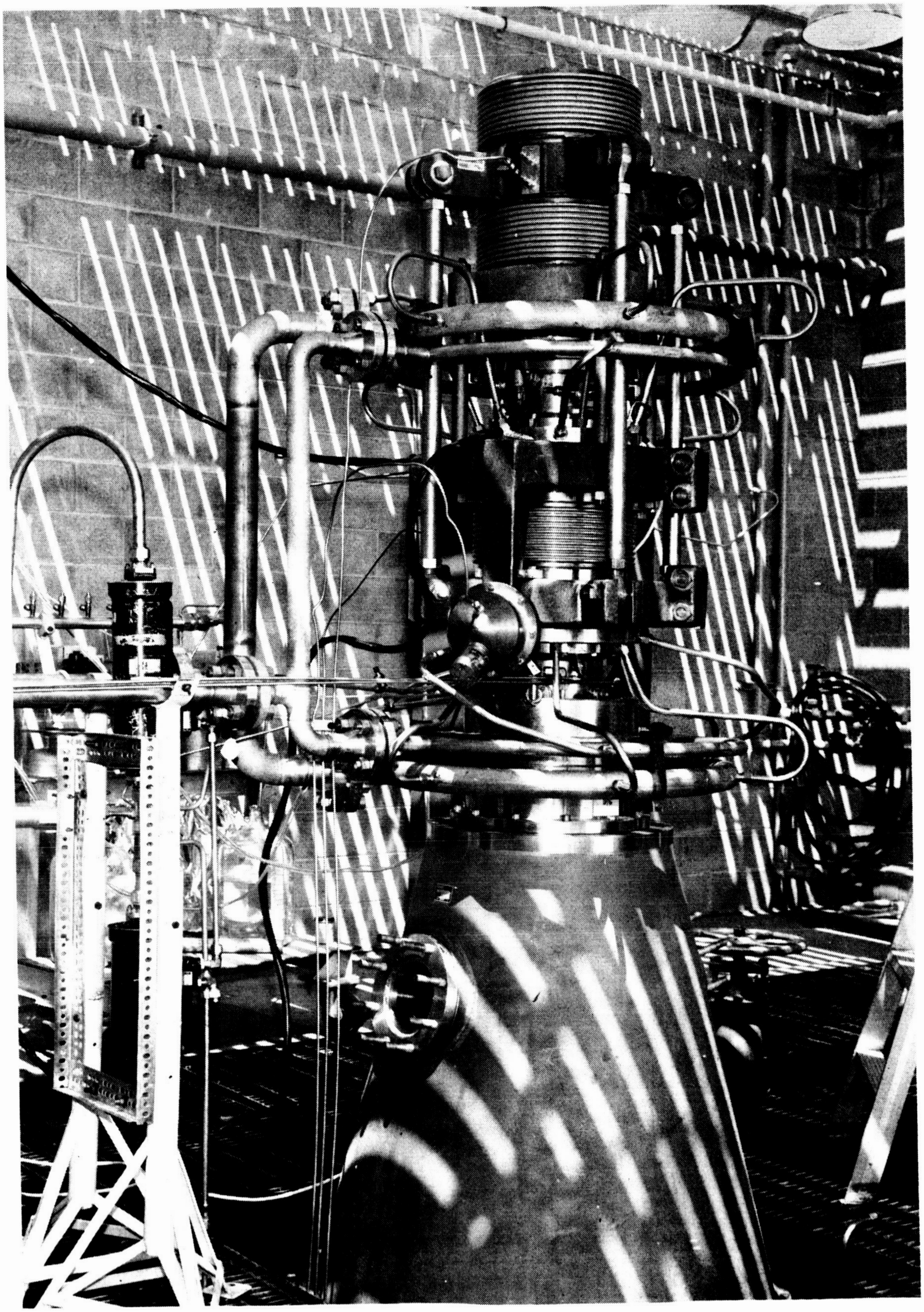

Figure 12

Test Stand, Power Transmission Tester

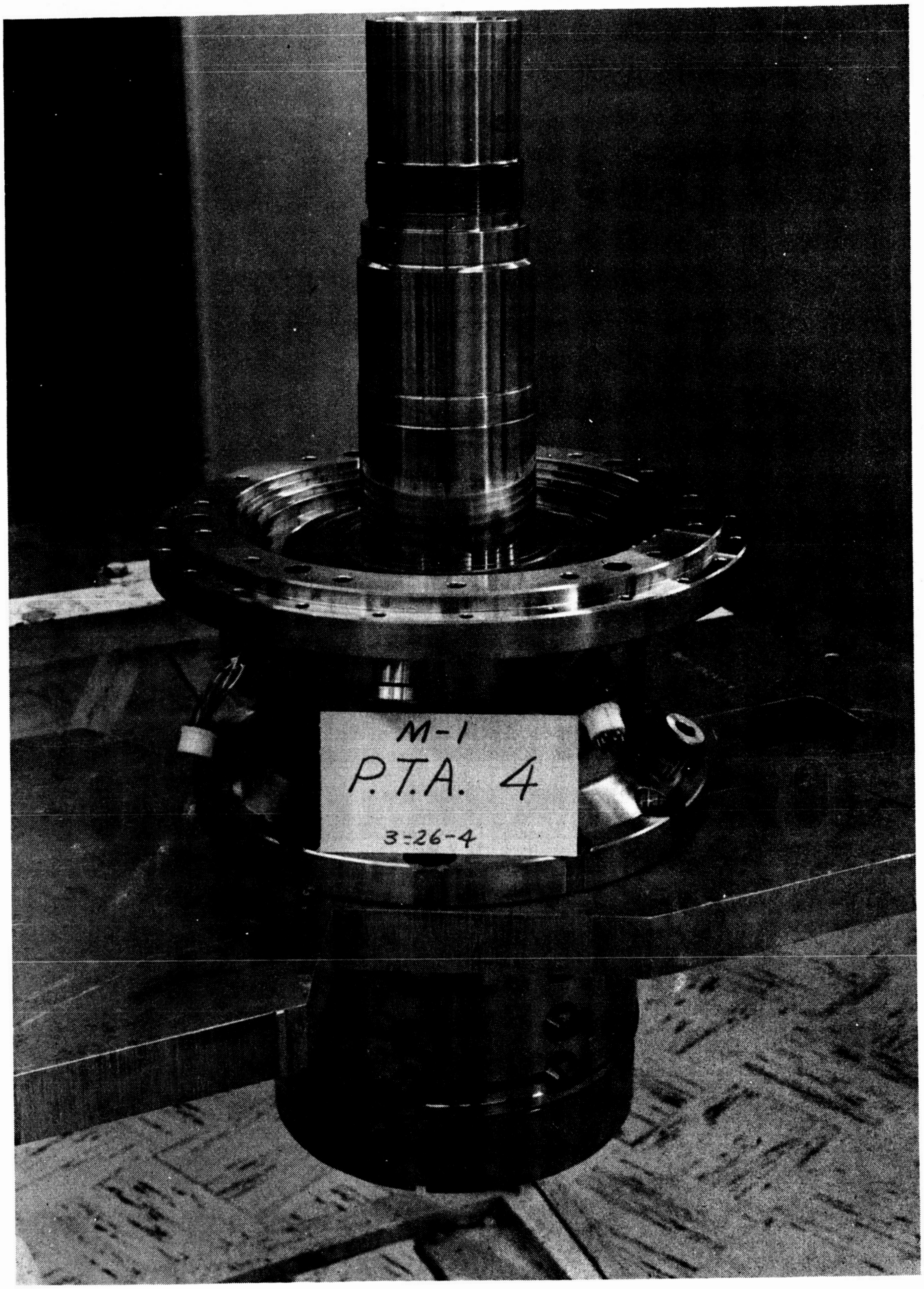

Figure 13

Single Power Transmission Assembly

(b) Motor-Driven Tester

Speed control of the motor-driven tester was maintained by manually controlling motor current and input frequency based upon visual observation of a digital readout tachometer. Because this speed control system's response characteristics were also dependent upon the reaction time and judgement of the operator, transient load tests were again impractical and testing was limited to steady load tests.

Acceleration was automatically controlled to a pre-set rate but was limited to a maximum of 2000 rpm/sec.

Deceleration was accomplished by switching off the motor current and allowing the tester to coast to a stop. No emergency shutdown system was provided.

(c) Power Transmission Tester

The power transmission tester speed was automatically controlled by a closed loop feedback circuit that monitored shaft speed and controlled the steam turbine inlet pressure. Maximum speed variations were limited to less than 100 rpm when a load was suddenly applied or removed.

Acceleration was accomplished by initially accelerating the flywheel to full speed and then activating the planetary gear system over a selected time interval. The maximum acceleration obtainable was 32,000 rpm/sec.

Deceleration was accomplished by simultaneously reducing turbine inlet pressure and braking the high-speed shaft to a stop. No emergency shutdown system was provided, but a shear-pin coupling disengaged the drive from the tester in the event of mechanical binding within the tester.

(2) Loading

Axial and radial load control was basically the same for all testers and was manually controlled by regulating hydraulic actuation pressure. The slow response characteristics of the hydraulic systems severely limited the transient load test capability.

(3) Coolant Pressure and Flow

Coolant flow rates and pressures were controlled by manually pre-set supply tank pressure and fixed line orifices; thus, the turbopump conditions of speed-dependent coolant supply pressure and flow rate were not simulated in any of the testers.

b. Measurements

(1) Pre-Test and Post-Test Dimensional Inspection

Bearing, shaft, and housing dimensions were taken before and after each test series. Gross dimensions, such as shaft diameter, bearing bore, and bearing outer diameter, were measured by conventional inspection equipment under rigidly controlled temperature conditions. Internal bearing geometry measurements were also taken under controlled environmental conditions in a laboratory; equipment capable of measurement to the nearest millionth of an inch was used. Ball size and size variations were the most useful dimensions because they gave a good indication of bearing wear and life expectancy. Dynamic contact angle measurements were not as useful as planned in determining load sharing because the wear paths were typically difficult to associate with a particular load; this resulted from the several loads and startup speed/load relationships encountered with each assembly. Typical pre-test and post-test dimensional records of a distressed bearing are given in Appendixes A and B.

Shaft runout and bearing drag torque were measured at assembly and during each test series. Bearing drag torque under known applied loads was a good indication of ball or race distress (Figure 14).

(2) Data Acquisition

Speed measurement was essentially the same for all testers and was made by a magnetic pickup mounted over a notched surface on the shaft. Speed was displayed on both a digital readout device and a strip chart.

Bearing load data were acquired through three basic systems: external load cells, pressure acting upon the actuator piston area, and internal axial load cells. The first two methods are well-developed conventional techniques; however, the internal load cell system is worthy of special note. This system, as used in the turbopump, consisted of a thin wall cylindrical Inconel spacer with eight strain gages bonded to the outer diameter, arranged in a self-temperature-compensating Wheatstone bridge. The results of the load cell bench tests showed that output was little affected by either bending loads or temperature changes, and total calibration data scatter (for all effects including supply variations) was less than $\pm$ 4%. However, little useful data was obtained from the load cell during actual bearing tests because severe electrical connector problems introduced changing-line resistances to the circuit.

Bearing vibrations were measured by internal accelerometers mounted in contact with the bearing outer races (Figure 15). However, no useable bearing vibration data were obtained because of similar inadequate connector performance.

Bearing temperature (Figure 16), coolant flow rate, pressure, temperature, and dynamic torque were measured by conventional means; all proved to be useful safe-operating criteria.

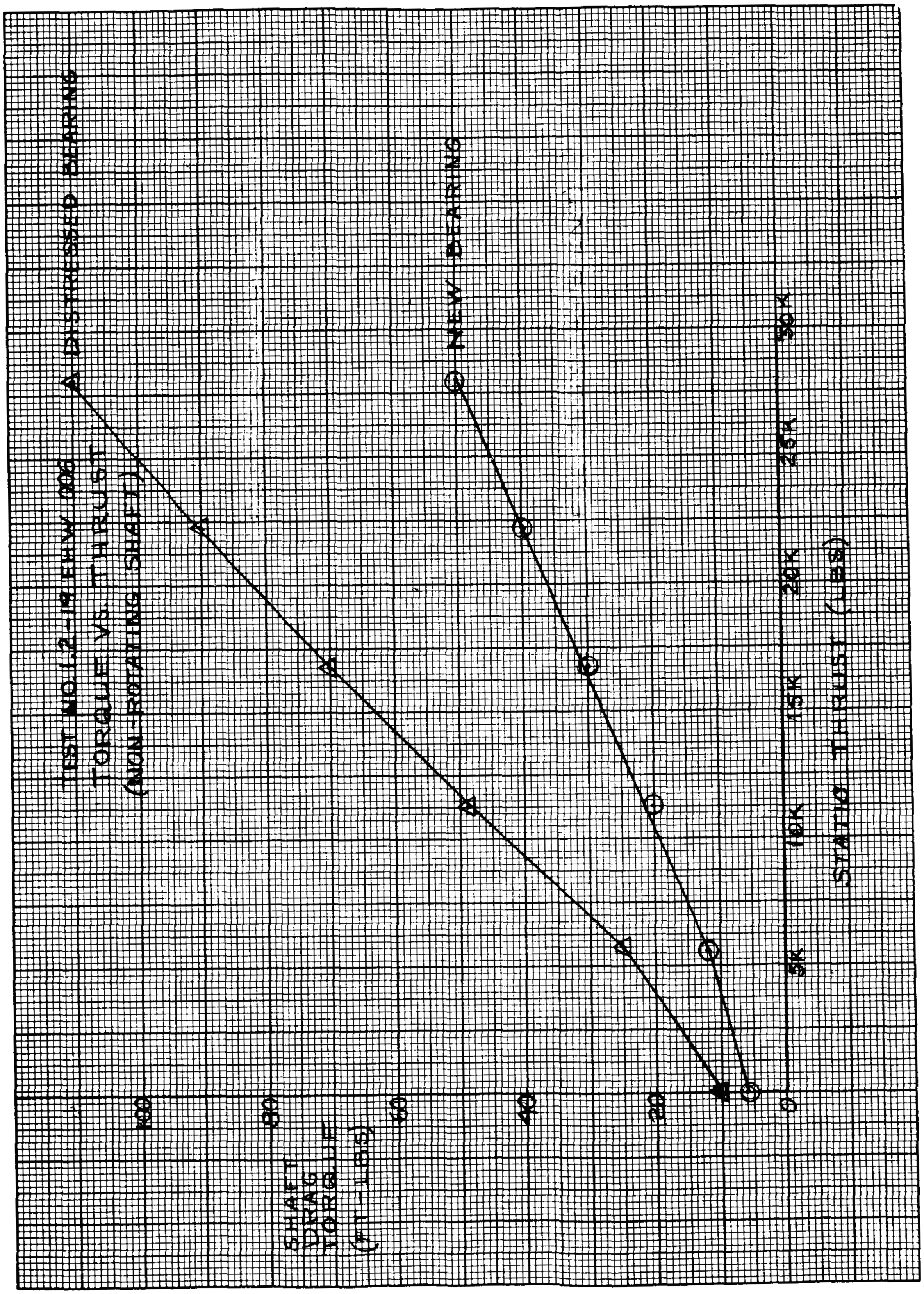

Figure 14

Drag Torque vs Thrust

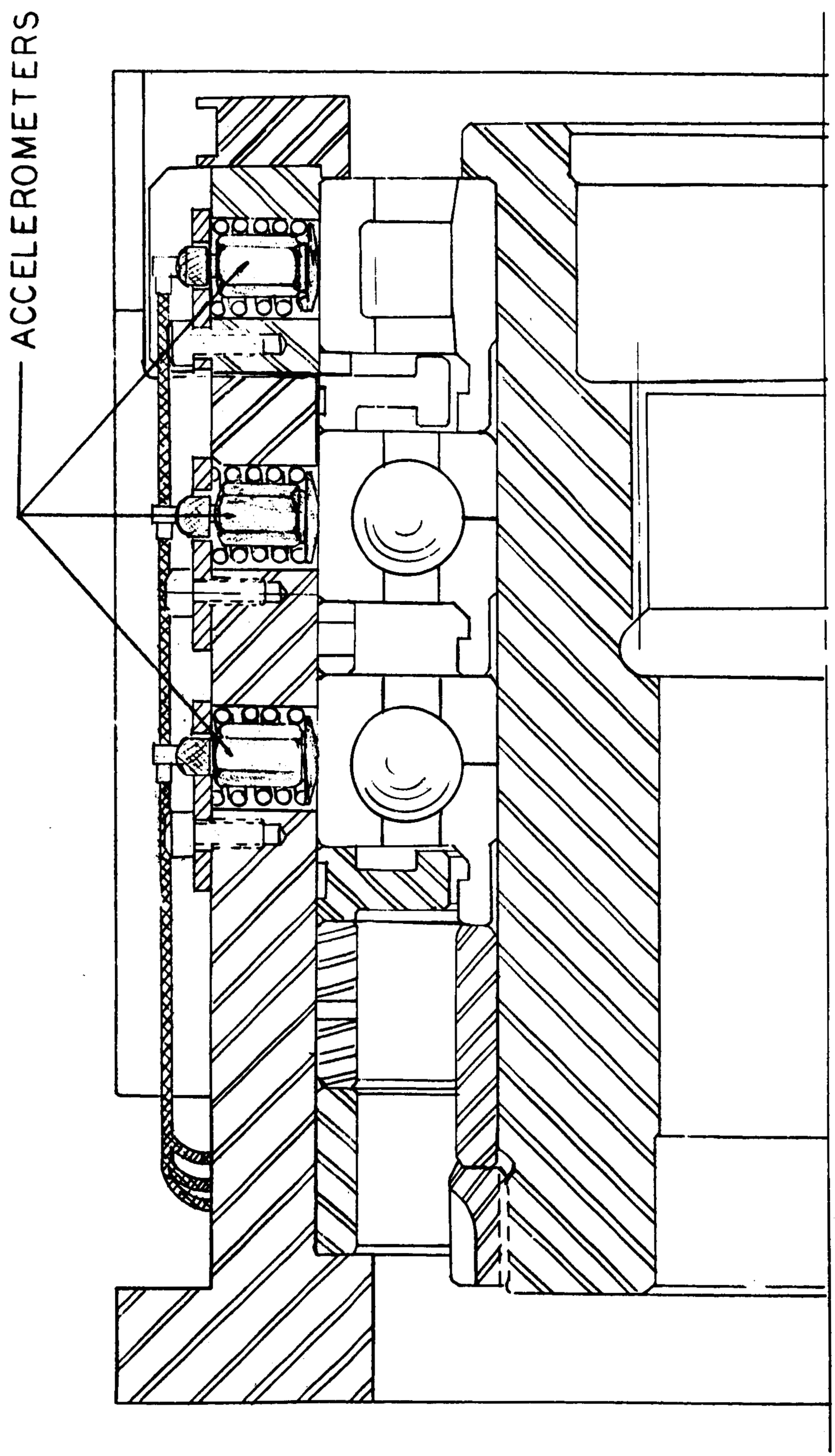

Figure 15

Accelerometer Location

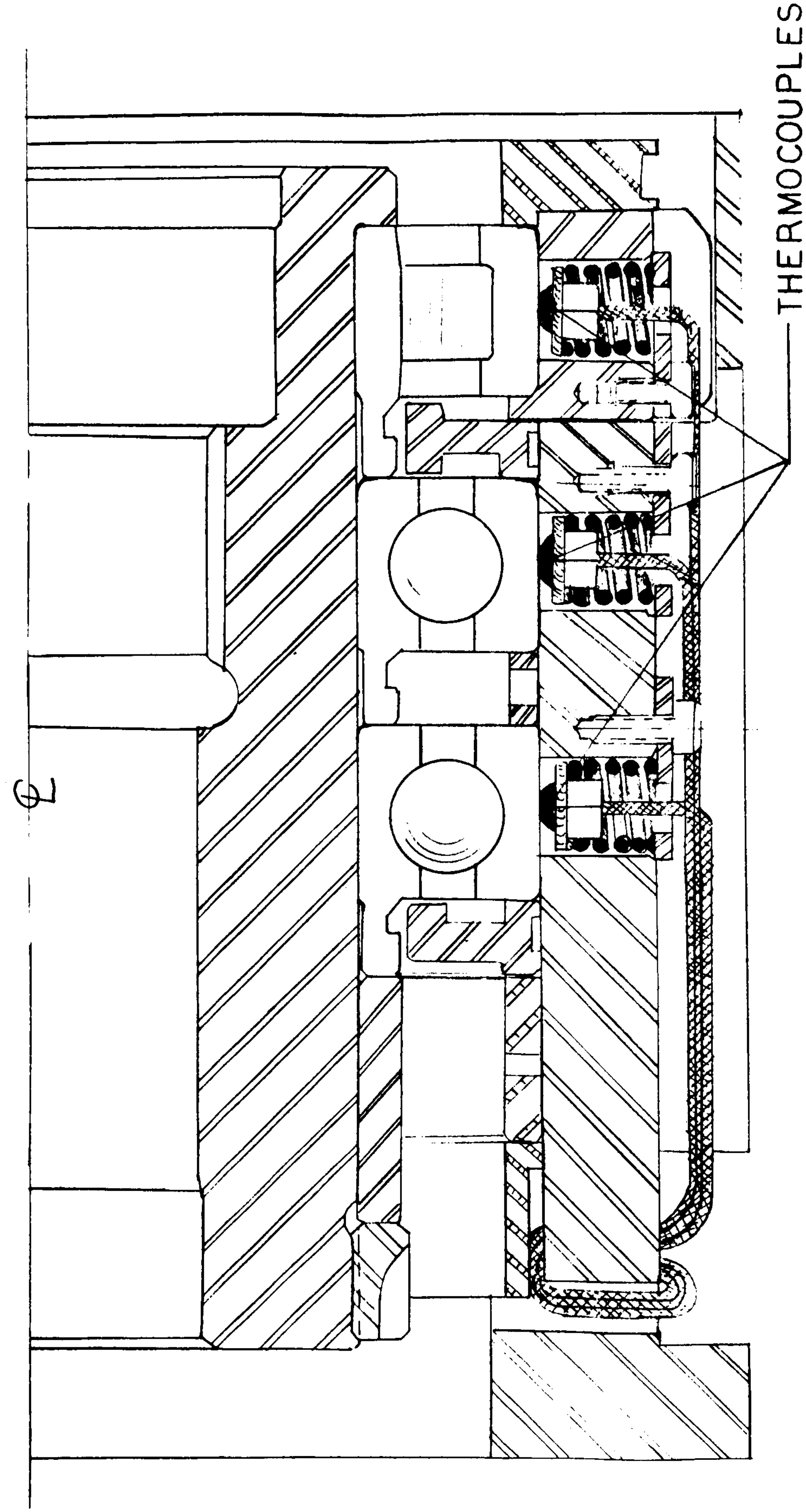

Figure 16

Thermocouple Location

c. Test Procedure

(1) Turbine Drive Testers

The pre-test and childown procedures were as follows for the single bearing tester and the acceleration tester:

(a) Maintain 120°F gaseous nitrogen purge for a minimum of one hour prior to bleed-in.

(b) Bleed in liquid oxygen for 15 min or until bearing temperatures reach -270°F, whichever is longer.

The test procedure varied with the tester and was as follows:

1 Single Bearing Tester (see Figures 3 and 4)

a Set thrust pre-load at 1000 lb. Set desired coolant flow and inlet pressure.

b Initiate test.

c Adjust speed to desired value.

d Increase thrust load to desired level and run steady state. Visually monitor speed, thrust, and bearing temperature.

e Terminate test by decreasing turbine pressure.

f Simultaneously decrease thrust load to pre-load limit.

g With speed at zero, decrease loads, coolant flow, and pressure to zero.

h Hot purge the bearing cavity at 120°F until bearing temperatures reach 70°F.

Unscheduled test termination limits were: speed exceeding 10,000 rpm; thrust load exceeding 20,000 lb; or bearing temperature reaching 200°F or changing rapidly.

2 Acceleration Tester (see Figures 5 and 6)

a Set desired thrust and radial loads.

b Set turbine pressure for desired acceleration rate with the valve closed.

c Set desired coolant flow and inlet pressure.

d Initiate test by opening turbine pressure valve.

e Operate until speed stabilizes.

f Terminate test by closing turbine pressure valve.

g With speed at zero, decrease loads, coolant flow, and pressure to zero.

h Hot gas purge bearing cavity at 120°F until bearing temperature reaches 70°F.

Unscheduled test termination limits were: speed greater than 6500 rpm, or bearing temperature reaching -200°F or changing rapidly.

(2) Motor Driven Tester (see Figures 7 and 8)

The general procedures for roller bearing (Figure 10) tests and thrust bearing (Figure 9) tests using the motor-driven tester were the same with the exception of not applying thrust loads in the roller bearing tests.

The following procedure is for a thrust bearing test:

(a) Purge test head and seal cavity with gaseous nitrogen at ambient temperature and 50 psig for one hour prior to test.

(b) Bleed-in coolant to test head and maintain 10 gpm flow until bearing temperatures reach -200°F maximum.

(c) Set radial pre-load at 1000 lb. Set thrust pre-load at 5000 lb.

(d) Set coolant flow rate and pressure to desired values and maintain until test termination.

(e) Start electric motor and increase speed to desired value.

(f) With speed stabilized, set desired thrust and radial loads.

(g) Operate at steady state; visually monitor speed, coolant flow, and bearing temperature.

(h) Simultaneously decrease speed, loads, coolant flow, and pressure to zero.

(i) Purge with nitorgen gas at 160°F until bearing temperature reaches 70°F.

Unscheduled test termination limits were: speed exceeding 10,000 rpm; coolant flow less than 30 gpm; or bearing temperature reaching 200°F or changing rapidly.

(3) Power Transmission Assembly Tester (See Figures 11 and 12)

The following procedure was used for the power transmission assembly tests.

(a) Maintain a dry gaseous nitrogen purge at 160°F into the tester at a rate of 1.0 lb/sec for 30 min prior to test. At the same time, maintain a vacuum in the seal vent cavity.

(b) Bleed-in coolant through the coolant lines at 60 psig and 20 gpm until bearing temperatures reach -270°F maximum. If the test is to include simulated turbine temperature, admit hot gas to the seal hot gas vent under the following conditions:

30 lb/hr Steam and 60 lb/hr Helium

Pressure of Mixture = 100 psi

Temperature at Inlet = 600°F

(c) Adjust bearing coolant flow rate and pressure to desired run level and adjust the pressure in the cavity between the two power transmission assemblies to 450 psia, leaving the turbine seal cavity at atmospheric pressure.

(d) Adjust bearing thrust and radial pre-loads.

(e) Initiate rotation and adjust speed. When desired speed is reached, increase thrust and radial loads to steady state levels.

(f) Operate at steady state. Monitor speed, coolant flow rate, bearing temperature, and bearing vibration.

(g) Terminate test by decelerating to zero speed while simultaneously reducing loads. With speed at zero, reduce coolant flow and pressure.

(h) Maintain a 5 psig gaseous nitrogen purge upon completion of tests.

Unscheduled test termination values were: speed greater than 5,000 rpm; coolant flow rate less than 35 gpm; bearing temperature over 180°F or rising at a rate greater than 5°F/sec; or a sudden rise in vibration level.

3. Test Results and Discussion

The test program was divided into the following four phases: a preliminary evaluation phase, during which the bearings of different manufacturers were surveyed to determine the most promising configuration; a qualification phase, in which the preferred-configuration ball and roller bearings were qualified for use in the turbopump at nominal operating conditions; a peripheral evaluation phase to demonstrate the capability of the bearings at "off-design" conditions of load and direction of load, coolant medium and coolant pressure; and a turbopump evaluation phase during which the applicability of component tests to the turbopump was demonstrated. A complete tabulation of bearing configuration, test conditions, and results for each test phase is given in Appendix C. A brief summary table and a discussion of the results of each test phase and category are given below.

a. Phase I--Preliminary Evaluation

(1) Category A--Single Thrust Bearings, Constant Speed

(a) Summary

Total Tests (Two Tests/Run)	40
Total Bearings Tested	10
Total Duration Accrued (sec)	10,550
Total Failures (Bearings not Reuseable)	1
Total Duration on One Bearing (sec)	3,454
Total Starts on Same Bearing	8
Typical Load on Same Bearing (Lb)	23,000
Maximum Load (Lb)	31,000
Duration at Maximum Load (Sec)	770

(b) Discussion

Single thrust bearing evaluation tests were conducted using the turbine driven tester shown in Figures 3 and 4.

Over-all performance of all bearings was excellent with the single failure clearly attributable to insufficient pre-test cooling of, and inadvertently low coolant flow to, the inboard bearing. Failure resulted from heavy internal (ball to race) interference caused by nonuniform cooling of the inner and outer races. The pre-test cooling procedure was modified to assure that all bearing race temperatures had reached -270°F or less prior to initiation of the test, and no further failures of that type were experienced. The minor ball and race distress noted after 370 sec of operation was caused by inadequate coolant flow because of excessive cage blockage[2]. The cages were modified by chamfering to improve the entrance condition to the contact surface, and two new bearings thus modified were subsequently tested for 3454 sec before similar surface distress was noted.

(2) Category B--Single Radial Bearings, Constant Speed

(a) Summary

Total Tests (Three Tests/Run)	12
Total Bearings Tested	4
Total Duration Accrued (Sec)	936
Total Failures	0
Total Duration on One Bearing (Sec)	234
Total Starts on Same Bearing	3
Typical Load on Same Bearing (Lb)	8850
Maximum Load (Lb)	8850
Duration at Maximum Load (Sec)	150

[2] Carney, J. A., Post-Test Analysis of M-1 LO_2 TPA Bearing P/N 288140, Report RMR 0177, Aerojet-General, 19 Feb 1964.

(b) Discussion

The single radial bearings were assembled into a carrier assembly as shown in Figure 10 and tests were conducted using the motor driven tester shown in Figure 8.

All bearings were in excellent condition at the conclusion of testing with no mechanical problems encountered. One of the bearings is shown after three tests in Figures 17, 18, and 19. However, discoloration of the roller end faces indicated a possible operational deficiency because the discoloration may have been caused by contamination of the rollers or races. More rigid cleanliness control was subsequently used and no further occurrences of this type were noted.

(3) Category C--Single Thrust and Radial Bearings, Acceleration Evaluation

(a) Summary

Total Tests (Two Tests/Run)	66
Total Ball Bearings Tested	6
Total Roller Bearings Tested	2
Total Duration Accrued (Sec)	1842
Total Failures	0
Total Starts on One Bearing	17
Typical Acceleration on Same Bearing (RPM/Sec)	8000
Typical Load on Same Bearing (Lb)	500
Maximum Acceleration (RPM/Sec)	8000

(b) Discussion

No problems were identified during the acceleration tests which were conducted using the turbine driven acceleration tester shown in Figures 5 and 6. However, tester control limitations, which were previously discussed under operational considerations, did not permit simulation of turbopump conditions of speed-dependent load and coolant pressure.

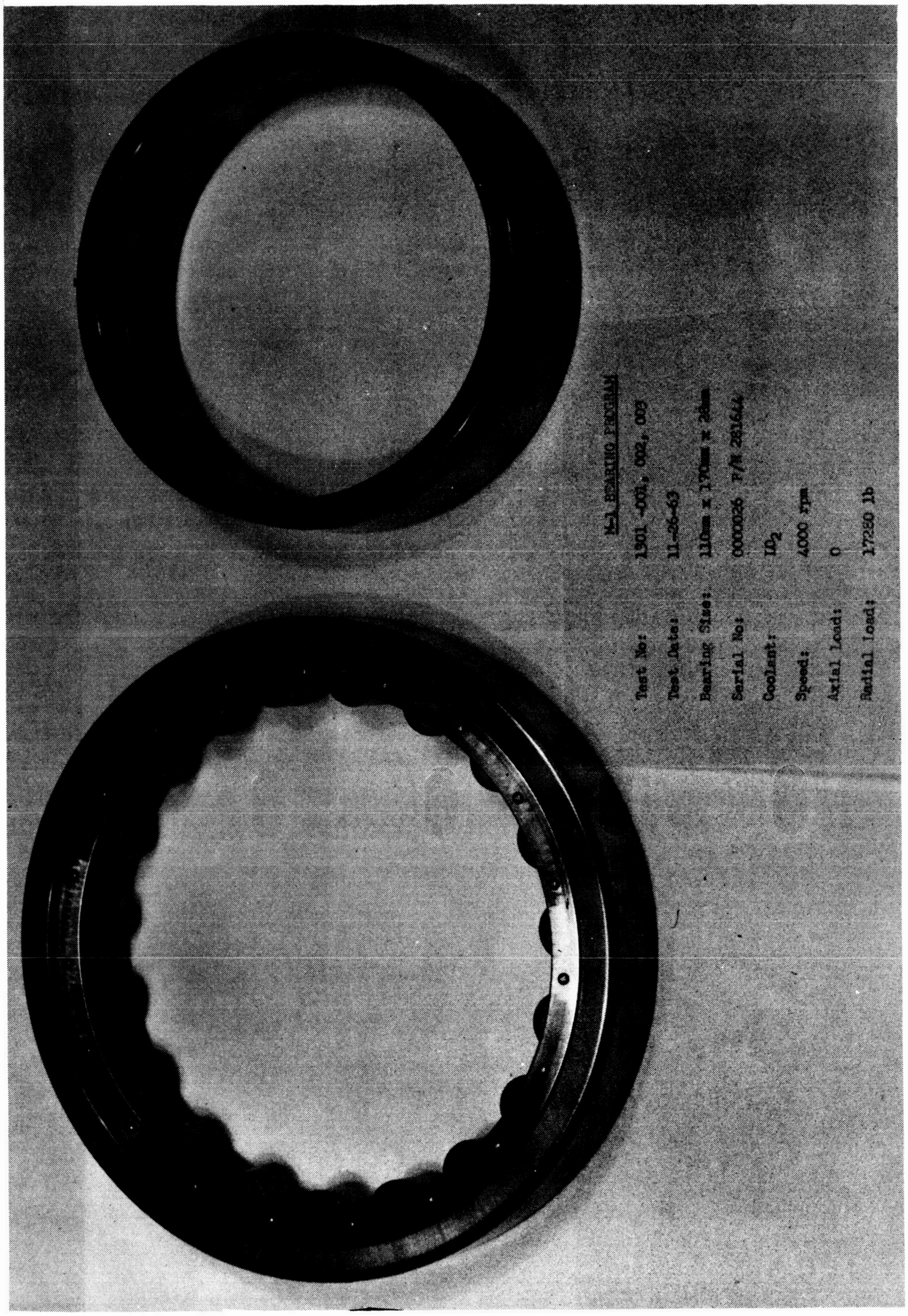

Figure 17

Radial Bearing

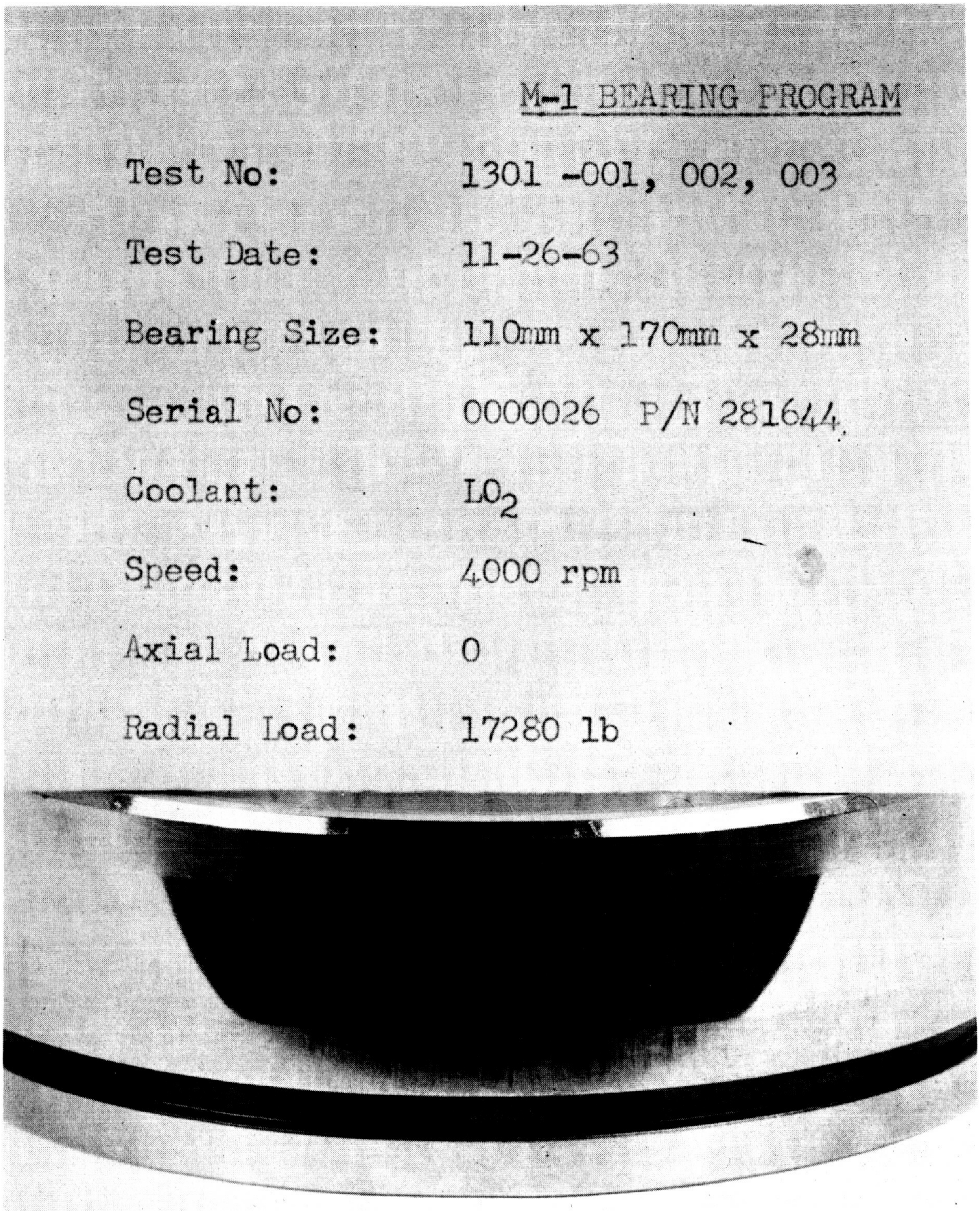

Figure 18

Radial Bearing Inner Race

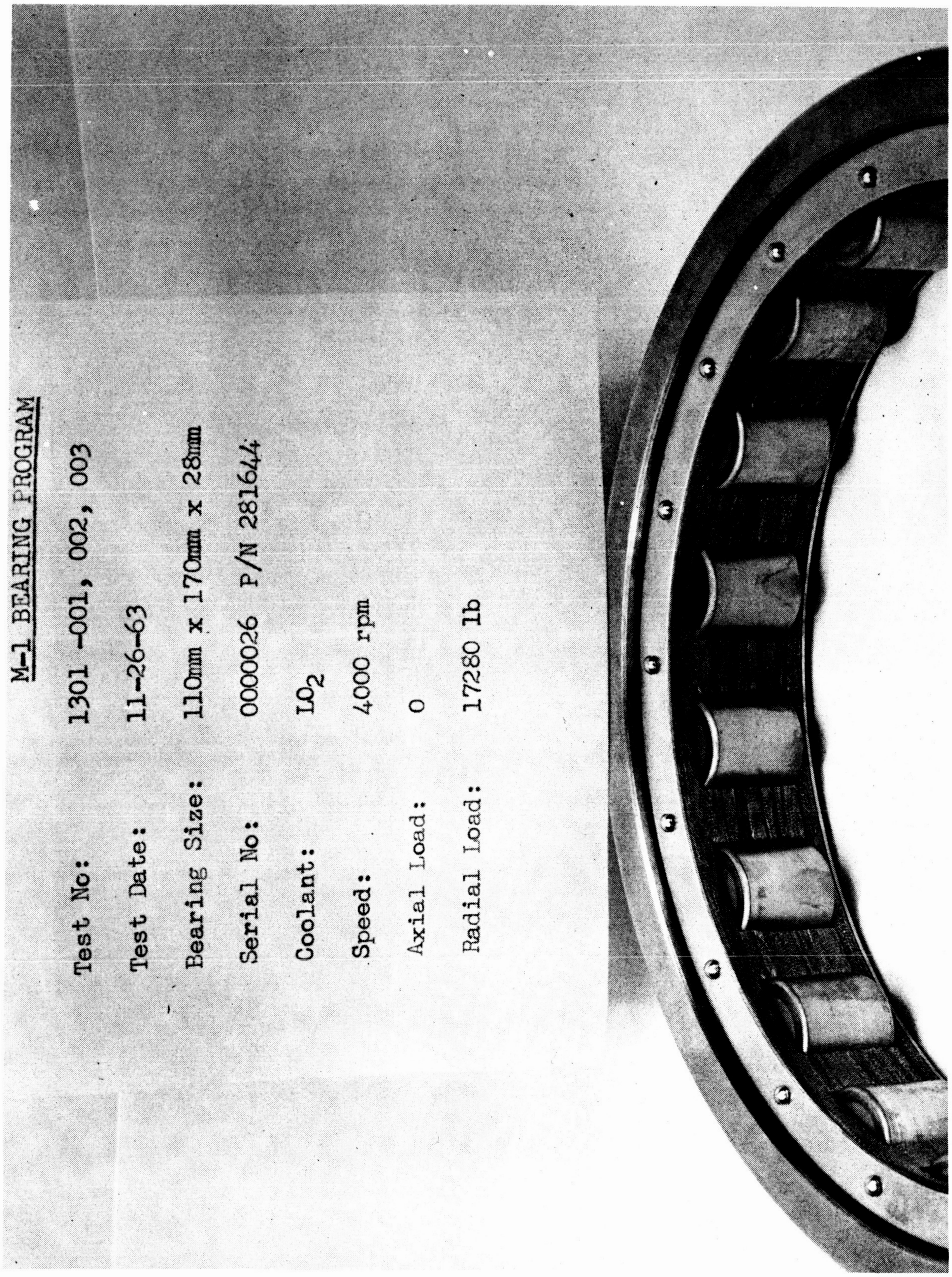

Figure 19

Radial Bearing, Rollers and Cage

(4) Category D--Single Radial Bearings and Single Thrust Bearings in Tandem, Power Transmission Tester (See Figures 11 and 12)

(a) Summary

Total Tests (6 Tests/Run)	144
Total Ball Bearings Tested	4 (2 sets)
Total Roller Bearings Tested	4
Total Duration Accrued with all Bearings (Sec)	10,600
Total Failures	2 (1 set)
Total Duration on Each Bearing (Sec)	1768
Total Starts on One Bearing	24
Typical Load on Same Bearings (Lb)	6700
Typical Load on Roller Bearings (Lb)	6000
Maximum Load on Ball Bearings (Lb/Set)	24,800
Maximum Load on Roller Bearings (Lb)	12,000

(b) Discussion

Performance of the bearings was excellent during this initial turbopump power transmission checkout test series, but faulty locknut installation in one power transmission (Figure 13) allowed the thrust bearing inner race halves to separate and fail because the ball made contact with the inner shoulder. No other significant operational or mechanical difficulties were noted.

b. Phase II-Qualification of Preferred Configuration

The very successful testing summarized above indicated that additional survey testing was not required. Therefore, the program was re-evaluated and effort was concentrated upon qualification of preferred bearings (P/N 281642, 281643 and 281644) for use in the turbopump. The following describes the qualification test phase.

(1) Category A--Tandem Thrust Bearings, P/N 281642, Motor Driven Tester (See Figures 7, 8, and 9)

(a) Summary

Total Tests (Two Tests/Run)	54
Total Bearings Tested	3
Total Duration Accrued (Sec)	11,320
Total Failures	0
Total Duration on One Bearing (Sec)	5660
Total Starts on Same Bearing	27
Typical Load on Same Bearing (Lb)	33,000
Maximum Load (Lb)	65,000
Duration at Maximum Load (Sec)	67

(b) Discussion

A primary objective of the qualification tests was to determine how well the tandem bearings shared the applied load. Examination of the bearings used in Buildup No. 1 definitely showed that some load sharing had taken place, but the actual sharing ratio was very difficult to determine because the several ball tracks generated at different applied loads overlapped to form a single, wide track. Therefore, the contact angles could only be estimated within a wide margin. A load sharing relationship of 66% to 34% was calculated upon that basis[3].

A second objective was to demonstrate safe-operation capability at 100% overload. Six tests were conducted at loads greater than 50,000 lb with no indication of failure.

A significant increase in required torque during the last tests of the third buildup indicated that failure was imminent. Examination of the bearings after disassembly showed that one bearing in each tandem set had overheated. The heating was probably caused by a combination of the very high

[3] Carney, J. A., Post-Test Analysis of M-1 LO_2 TPA Tandem Ball Bearings P/N 281642, S/N 18 and 32, Report RMR 0192, 27 Mar 1964.

thrust loads and cage wear. The bearings are shown after 5660 sec of test duration in Figures 20 through 29.

(2) Category B--Radial Bearings, P/N 281644, Motor Driven Tester (See Figures 8 and 10)

(a) Summary

Total Tests (Two Tests/Run)	52
Total Bearings Tested	4
Total Duration Accrued (Sec)	12,032
Total Failures	0
Total Duration on One Bearing (Sec)	6,461
Total Starts on Same Bearing	25
Typical Load on Same Bearing (Lb)	1000
Maximum Load (Lb)	17,700
Duration at Maximum Load (Sec)	234

(b) Discussion

Over-all performance of all bearings was excellent; no mechanical or operational problems of any kind were encountered.

(3) Category C--Tandem Thrust Bearings, P/N 281642, Power Transmission Assembly Tester (See Figures 11 and 12)

(a) Summary

Total Tests (Two Tests/Run)	18
Total Bearings Tested	2
Total Duration Accrued (Sec)	6564
Total Failures	0
Total Duration on One Bearing (Sec)	3282

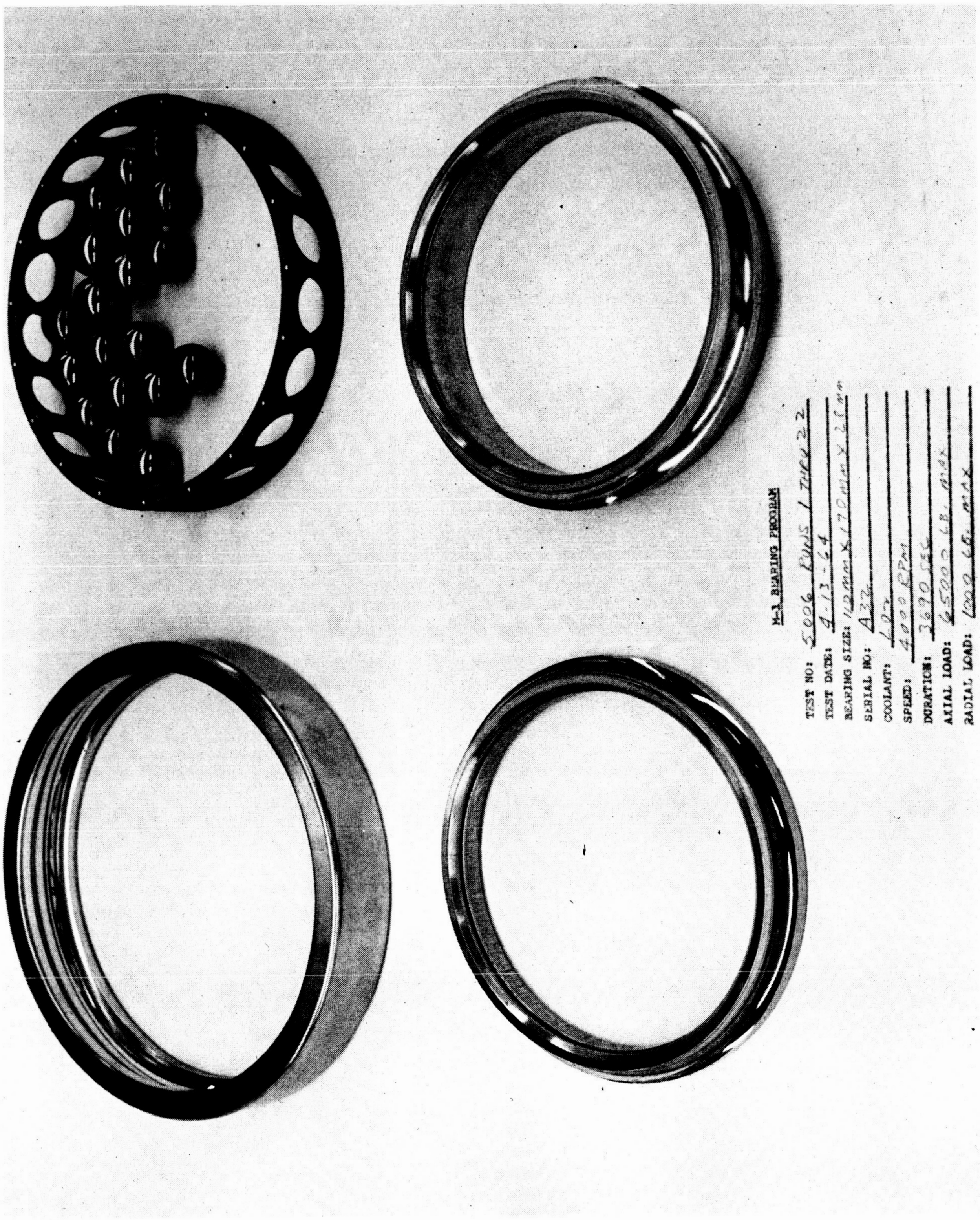

Figure 20

Thrust Bearing, Disassembled (S/N 32A)

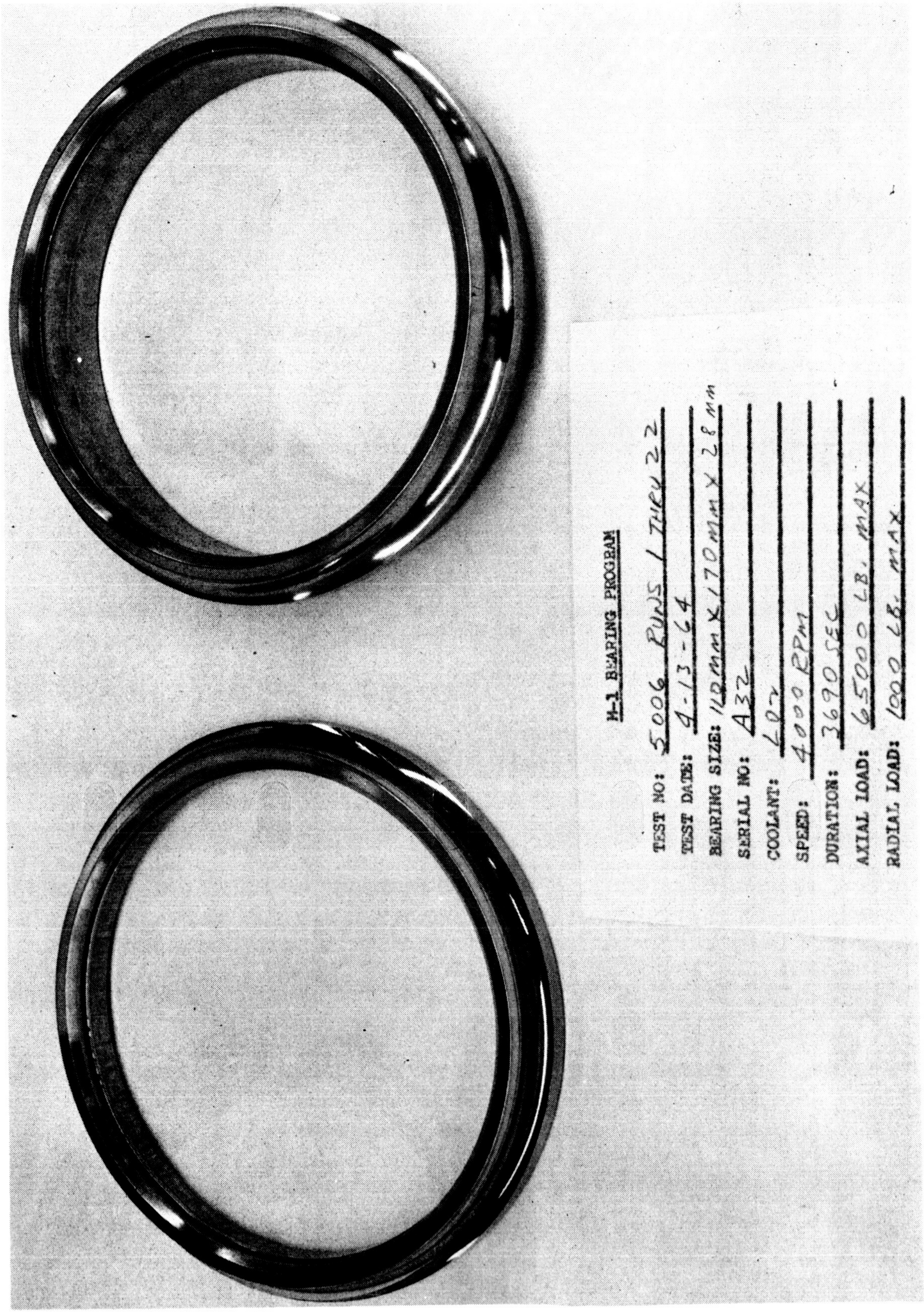

Figure 21

Thrust Bearing, Inner Races (S/N 32A)

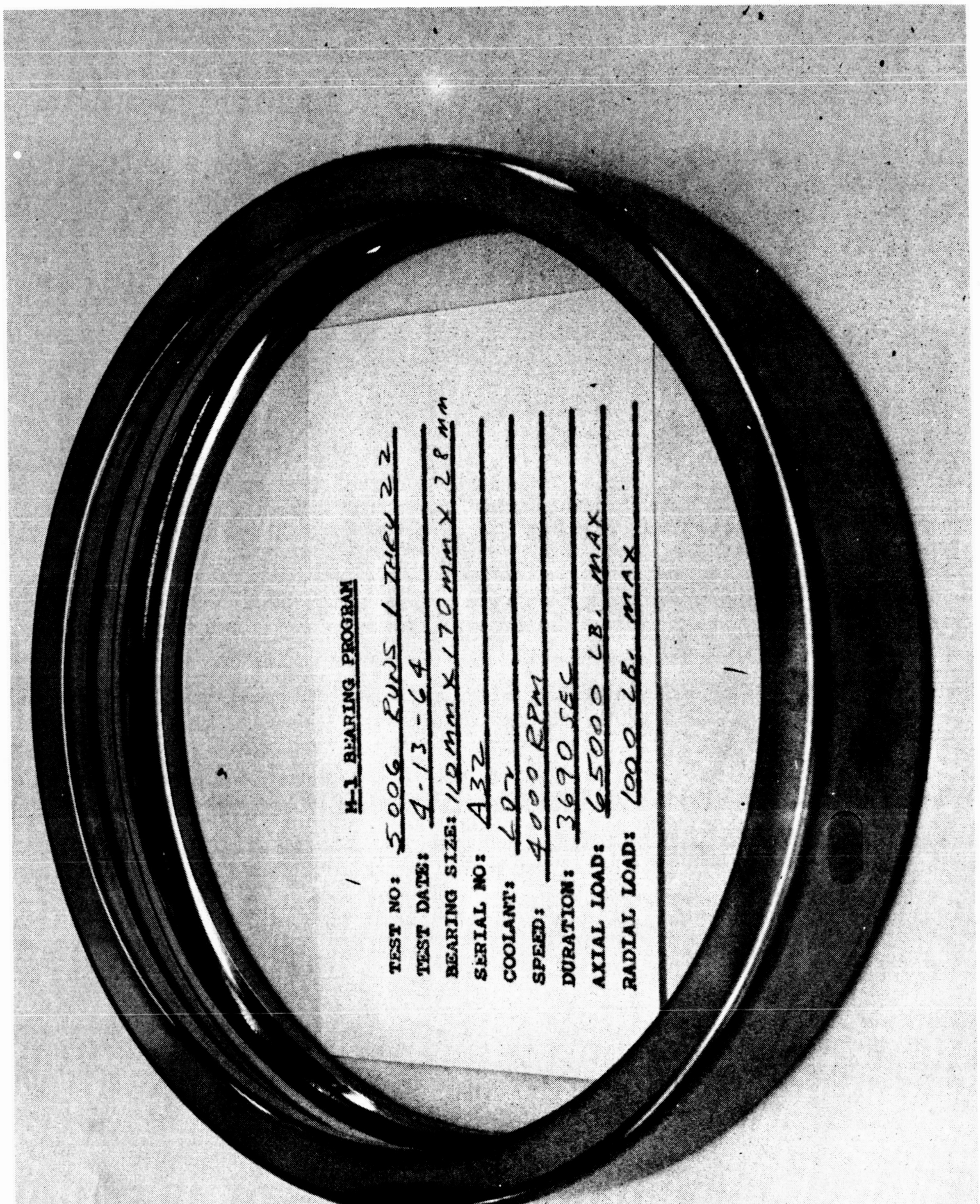

Figure 22

Thrust Bearing, Outer Races (S/N 32A)

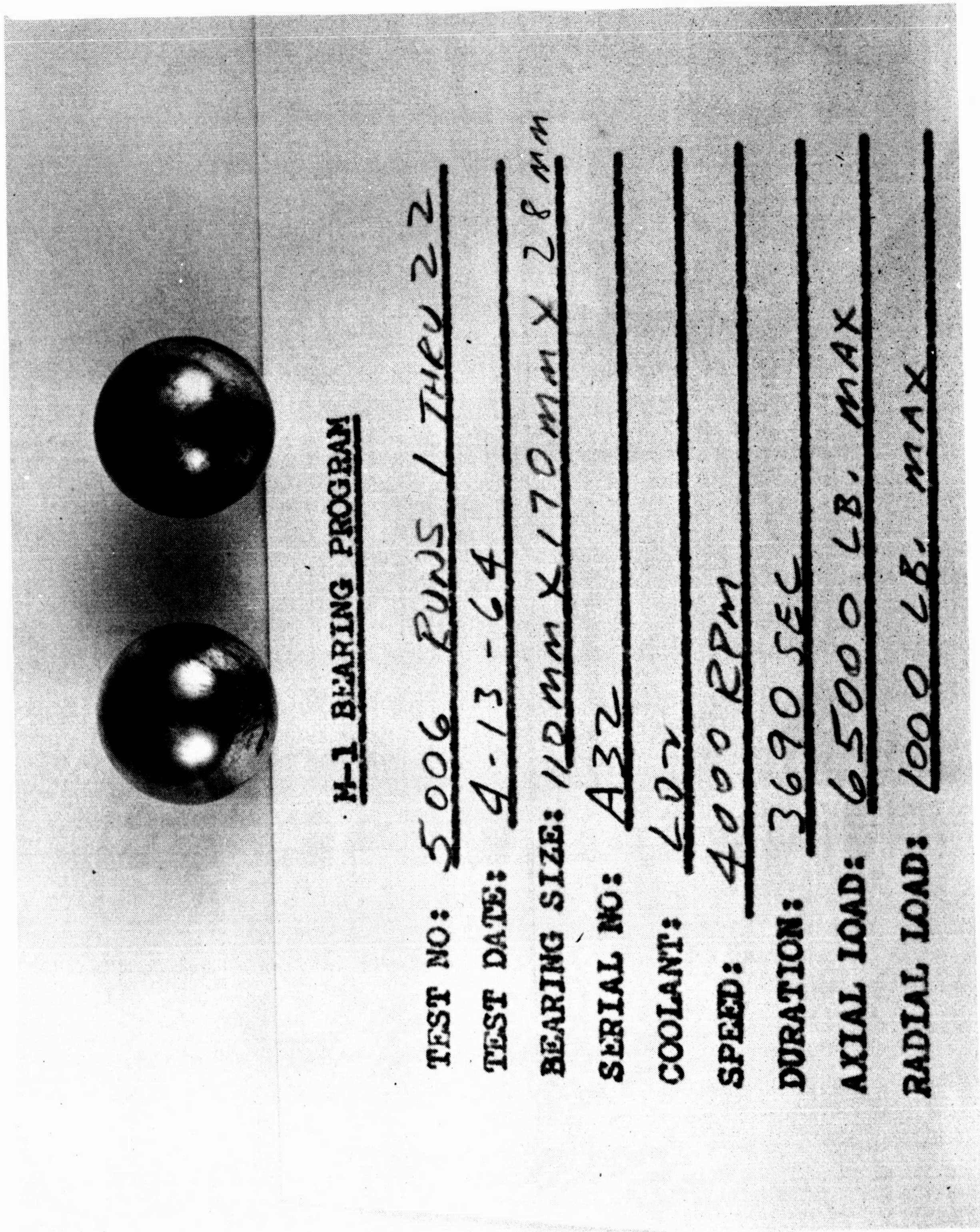

Figure 23

Thrust Bearing, Balls (S/N 32A)

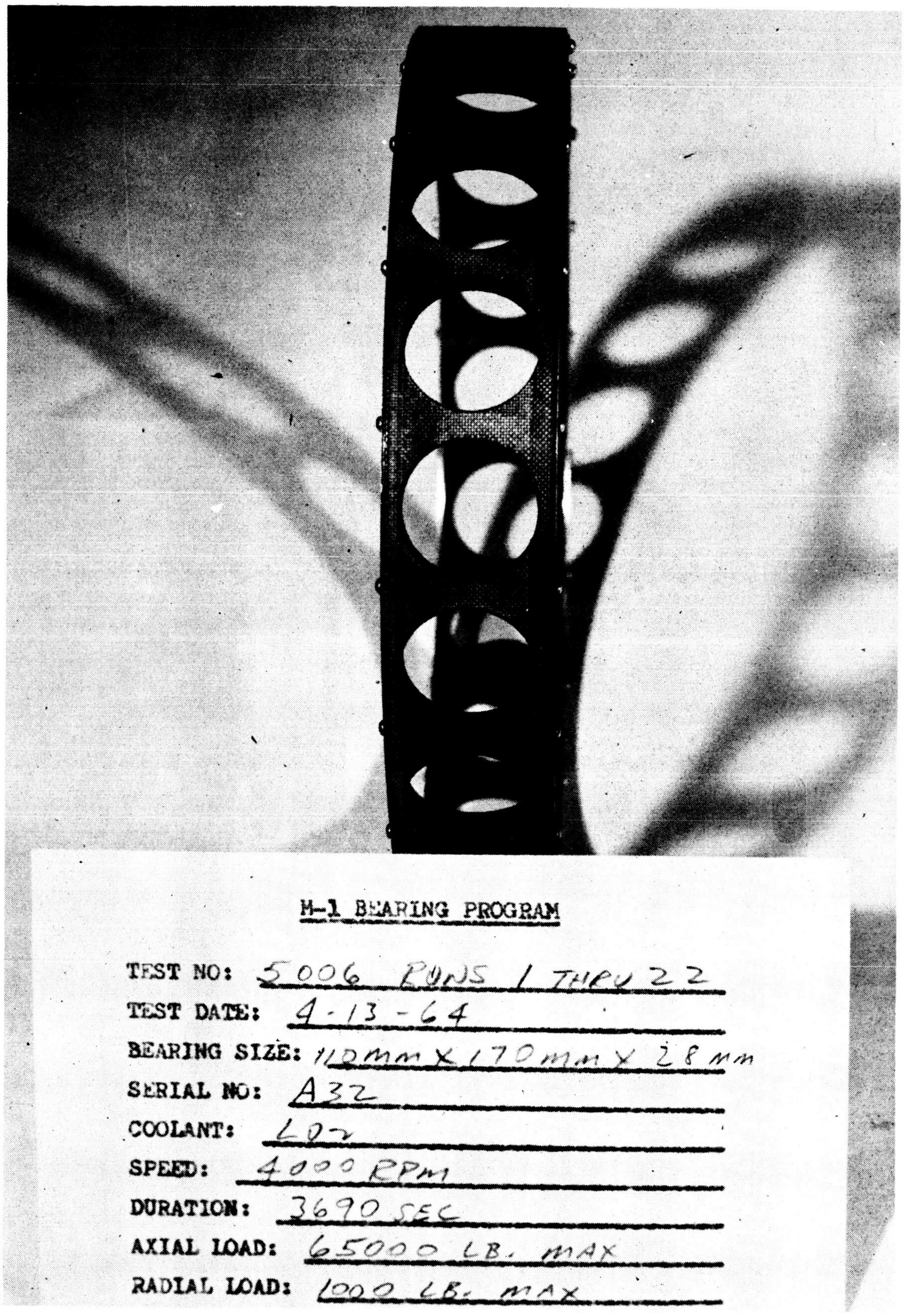

Figure 24

Thrust Bearing, Cage (S/N 32A)

Figure 25

Thrust Bearing, Disassembled (S/N 32B)

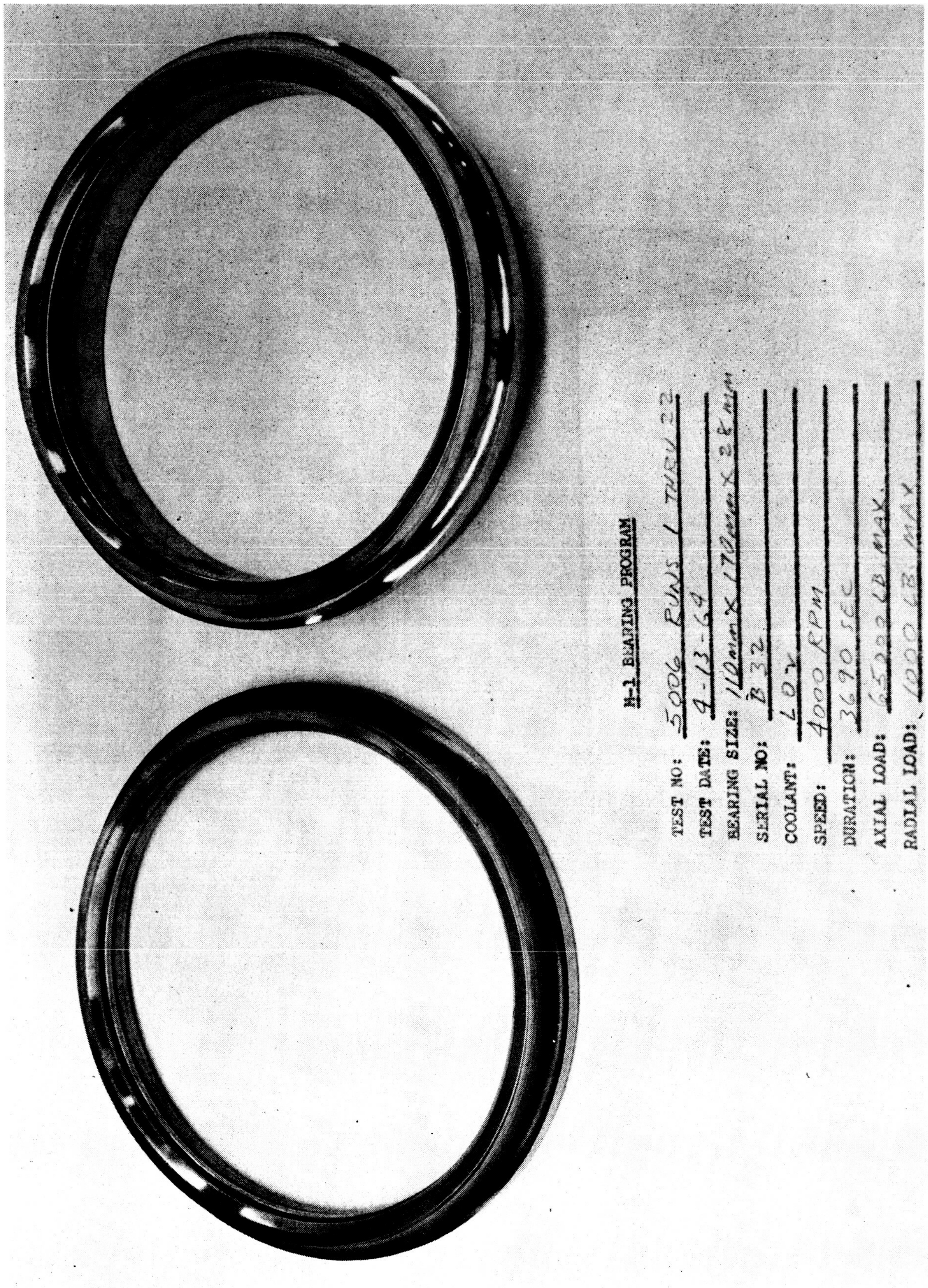

Figure 26

Thrust Bearing, Inner Races (S/N 32B)

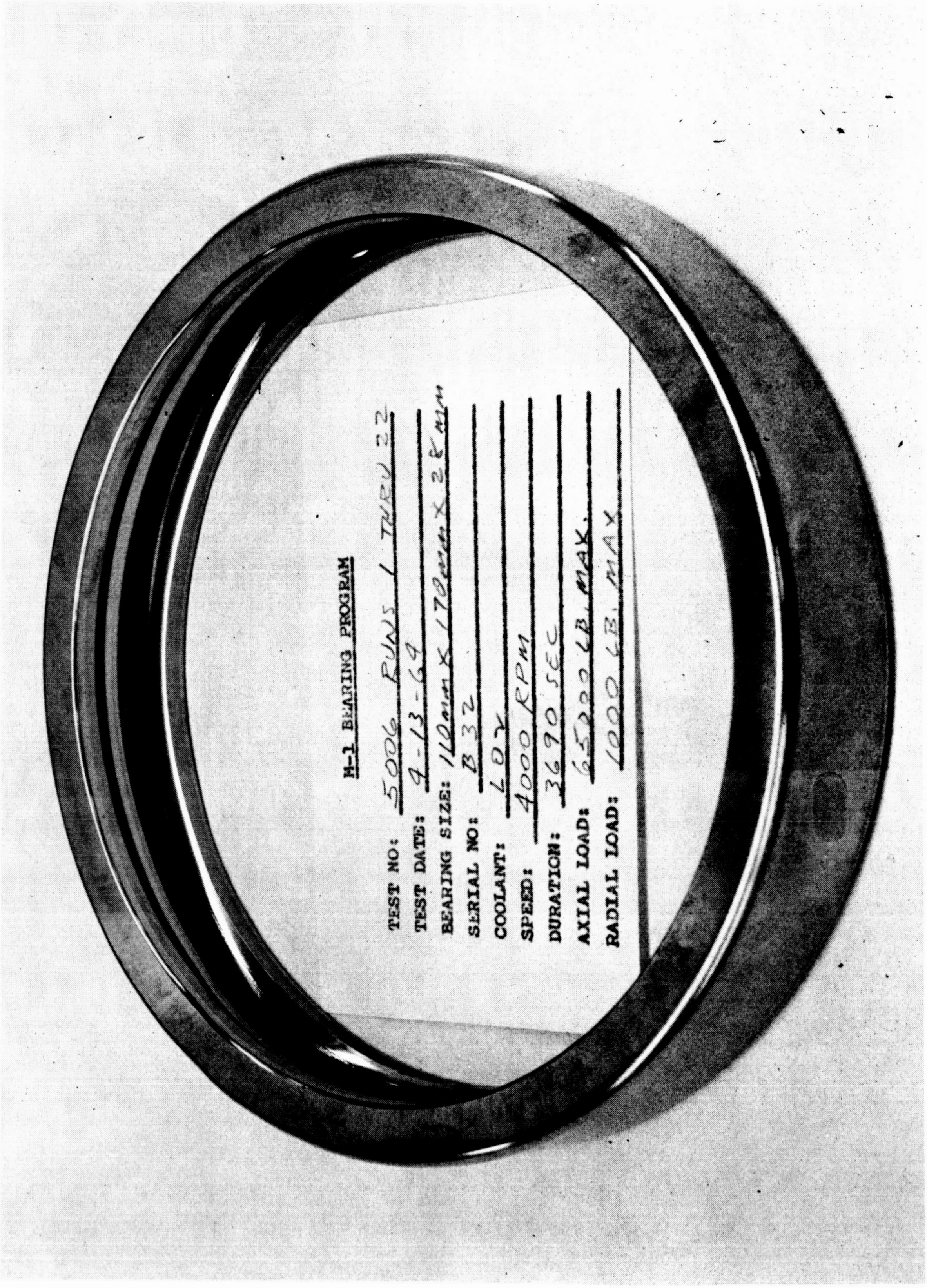

Figure 27

Thrust Bearing, Outer Race (S/N 32B)

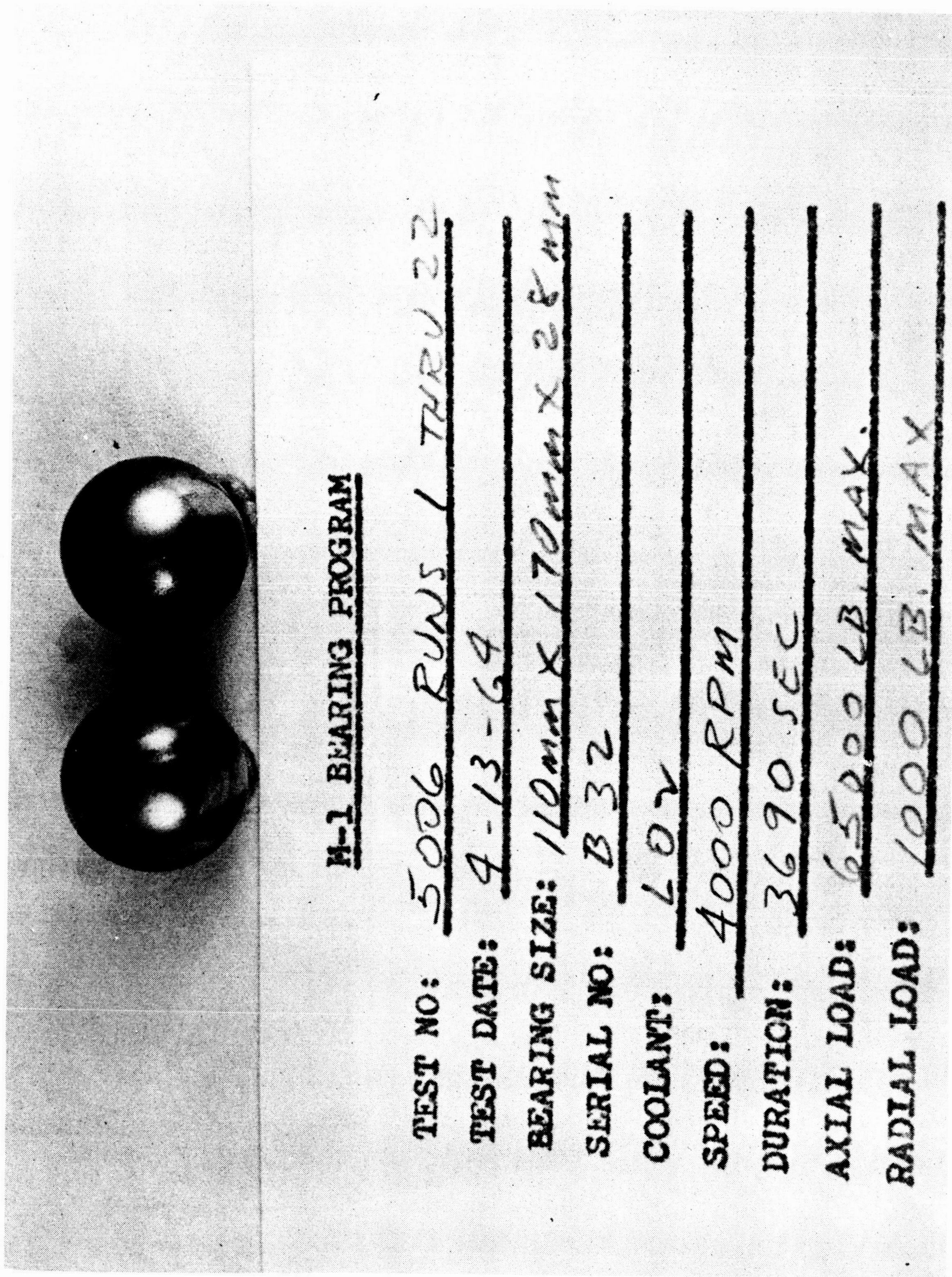

Figure 28

Thrust Bearing, Balls (S/N 32B)

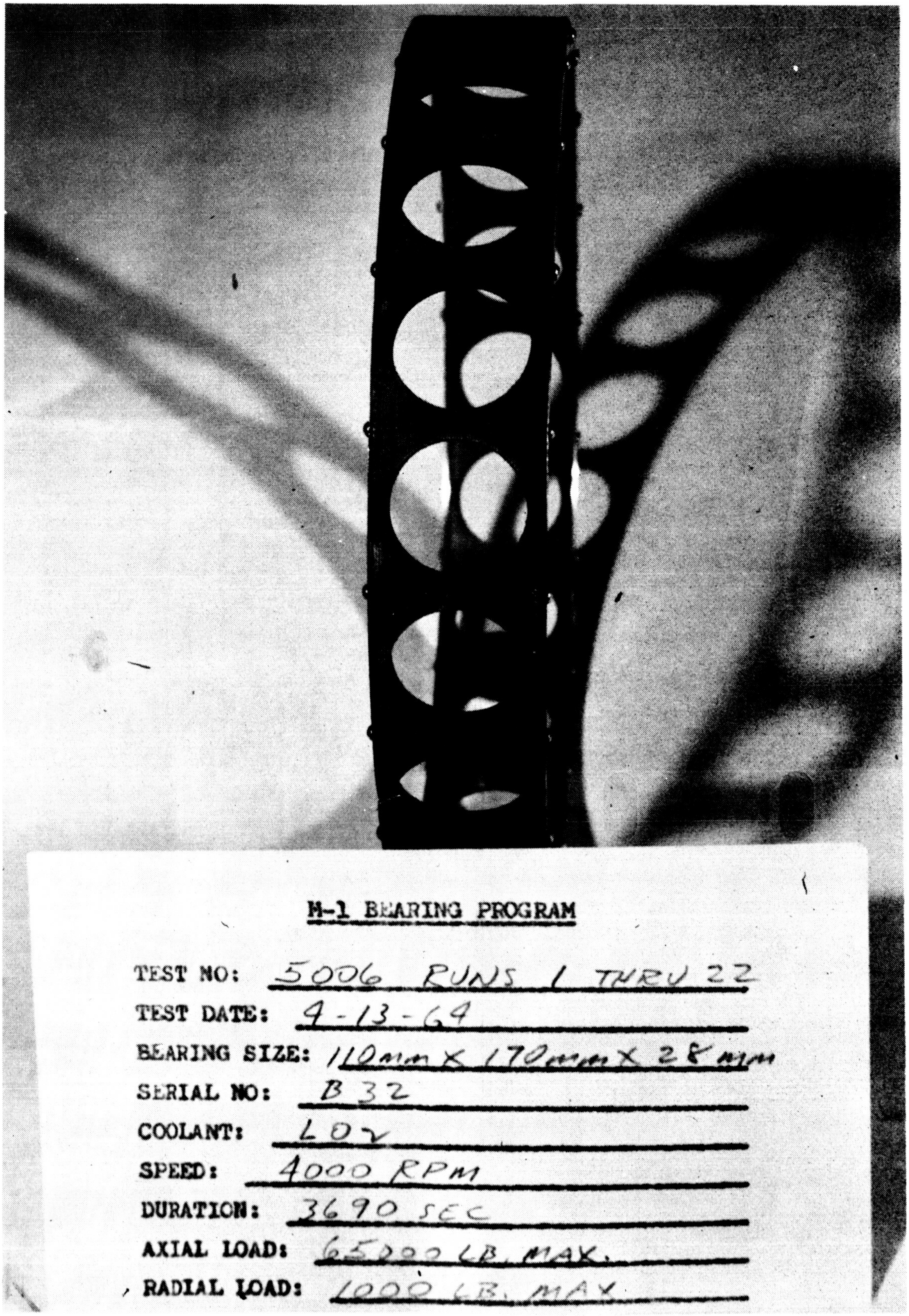

Figure 29

Thrust Bearing, Cage (S/N 32B)

Total Starts on Same Bearing	9
Typical Load on Same Bearing (Lb)	34,000
Maximum Load (Lb)	39,000
Duration at Maximum Load (Sec)	138

(b) Discussion

The bearings performed flawlessly throughout the entire test series. Post-test inspection of the bearings showed no visible or measurable damage.

(4) Category D--Radial Bearings P/N 281644, Power Transmission Assembly Tester (See Figures 11 and 12)

(a) Summary

Total Tests (4 Tests/Run)	36
Total Bearings Tested	4
Total Duration Accrued (Sec)	13,128
Total Failures	0
Total Duration on One Bearing (Sec)	3282
Total Starts on Same Bearing	9
Typical Load on Same Bearing (Lbs)	15,000
Maximum Load (Lb)	15,000
Duration at Maximum Load (Sec)	2470

(b) Discussion

Turbine heating was simulated for the final five tests of the series. Although the bearing temperature was approximately 10°F higher than in previous tests, no adverse effects were noted. The condition of all rollers and races was excellent at the conclusion of the tests.

c. Phase III - Peripheral Evaluation of Prototype Configuration (P/N 281642, 281643, and 281644)

The total success of the qualification testing led to a third redirection of the program. It was concluded that both the economical and technical interests of the program would best be served if the qualification testing at nominal turbopump conditions was discontinued. The program emphasis was placed upon evaluation of the preferred-configuration bearings at the peripheral operating conditions expected during the first turbopump test series.

The peripheral test phase was conducted primarily to evaluate the effects of high, reversed-thrust bearing loading at low speed while using liquid nitrogen as a coolant under possible boiling conditions. It appeared that the combined effects of poor load sharing caused by reversed loading and the different cooling characteristics of liquid nitrogen might constitute a hazard to safe turbopump operation.

(1) Category A - Tandem Thrust Bearings, P/N 281642, Reversed Load, Motor Driven Tester (See Figures 7, 8, and 9)

(a) Summary

Total Tests	19
Total Bearings Tested	2
Total Duration Accrued (Sec)	1554
Total Failures	0
Total Duration on One Bearing (Sec)	833
Total Starts on Same Bearing	7
Typical Load on Same Bearing (Lb)	30,000
Maximum Load (Lb)	33,000
Duration at Maximum Load (Sec)	61

(b) Discussion

Visual inspection of the test bearings, which were those loaded in reverse direction, showed no damage whatsoever; however, the slave bearing set showed signs of heating on the balls and races. It was believed that the discolored bearings were reuseable, but the tester was reassembled with new slave bearings so that the used bearings could be dimensionally inspected while still maintaining schedule requirements. The slave bearings were of the same configuration as the test bearings for the balance of the testing, thereby doubling the test experience for those tests.

The remainder of the tests were conducted without incident until the next to last test, during which, a sharp 40°F rise in bearing temperature was noted. A post-test bearing drag torque check performed with 20,000 lb applied load showed that torque had risen from 50 ft-lb to 85 ft-lb. A final test was conducted and again the high torque condition was noted although the sharp temperature rise did not recur. The test bearings showed signs of minor heat distress, but dimensional inspection proved they were reuseable. The test bearings after 833 sec of operation are shown in Figures 30 through 37.

It was concluded that a sharp rise in bearing temperature of approximately 40°F was a safe malfunction shutdown criterion, and that a 40 ft-lb increase in drag torque at 30,000 lb applied load was a useful indication of bearing distress. A further, more obvious conclusion was that the bearings would function in the expected turbopump environment for at least the intended cumulative turbopump test duration of approximately 200 sec.

d. Phase IV - Turbopump Evaluation

The successful completion of bearing testing at the component level provided the basis for the decision to test the bearings (P/N 281642, 281643, 281644) in the turbopump. Accordingly, two sets of bearing evaluation data with liquid nitrogen coolant are available from the two turbopump test series. These are discussed below.

(1) Category A - Reversed Load, Low Speed, Turbopump (See Figures 1 and 2)

(a) Summary

Total Tests	10
Total Duration Accrued (Sec)	197
Total Failures	0
Typical Thrust Load (Lb)	15,000/18,000
Maximum Thrust Load (Lb)	40,000
Duration at Maximum Load (Sec)	10

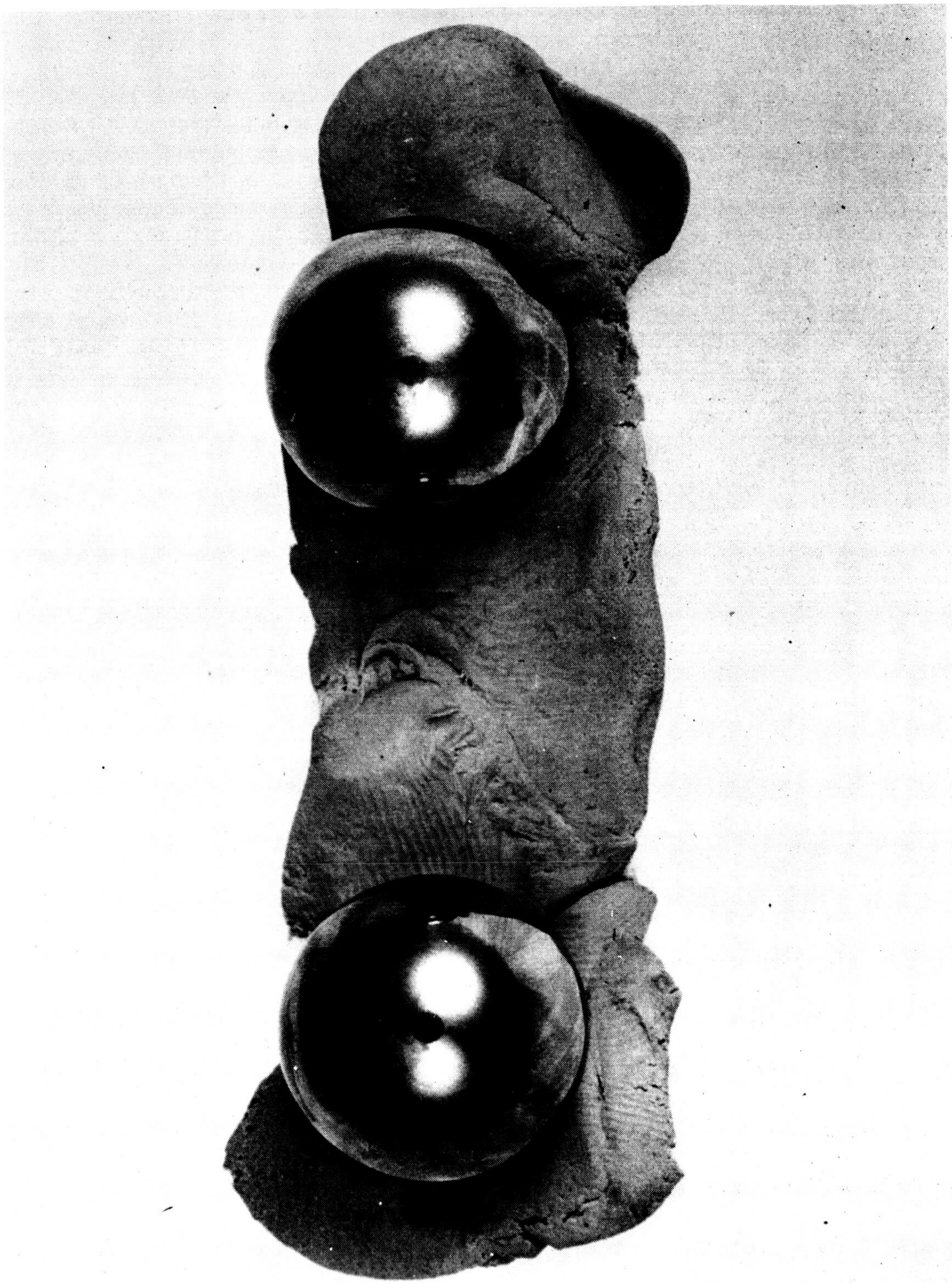

Figure 30

Thrust Bearing, Balls (S/N 52A)

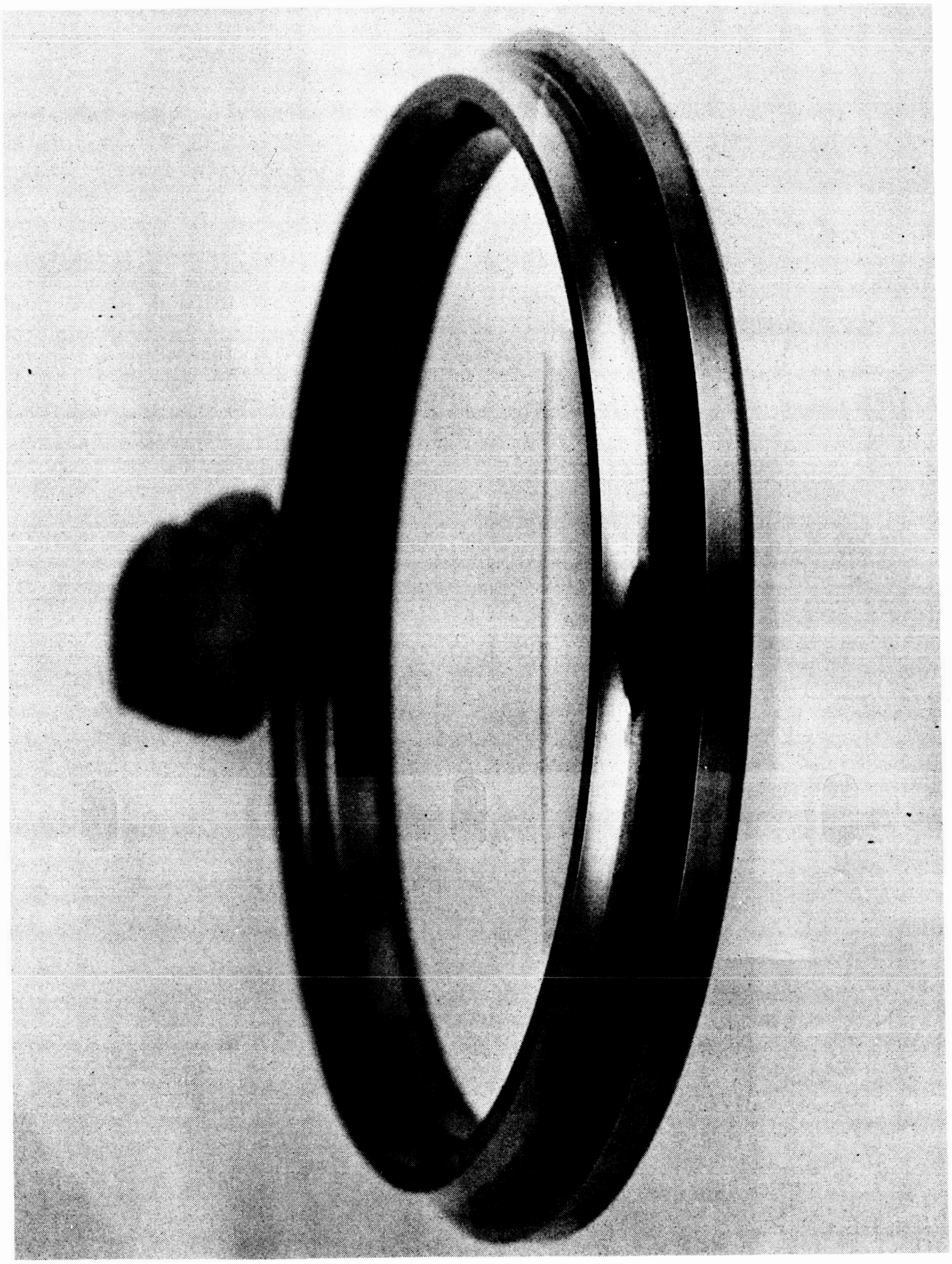

Figure 31

Thrust Bearing, Inner Race (S/N 52A)

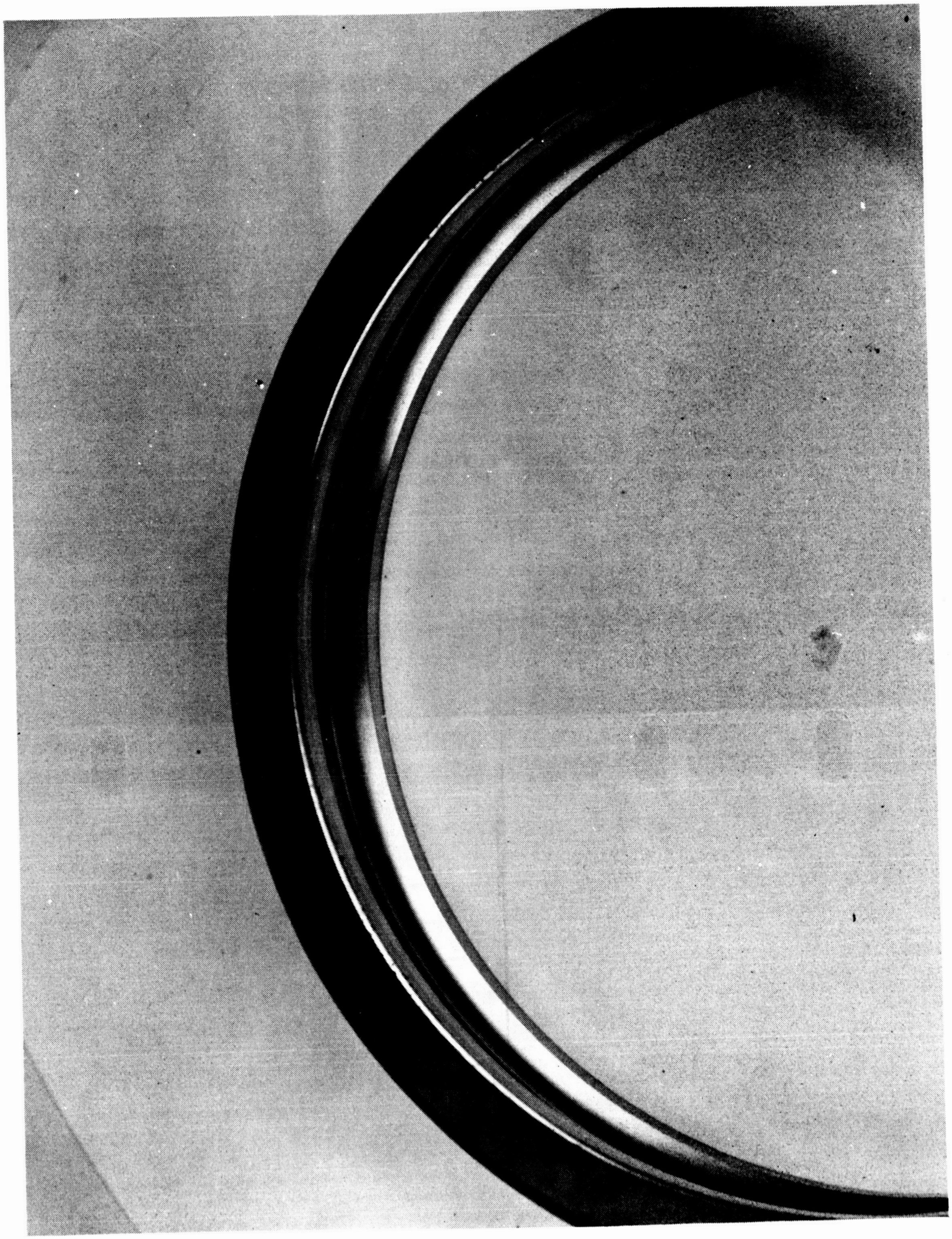

Figure 32

Thrust Bearing, Outer Race (S/N 52A)

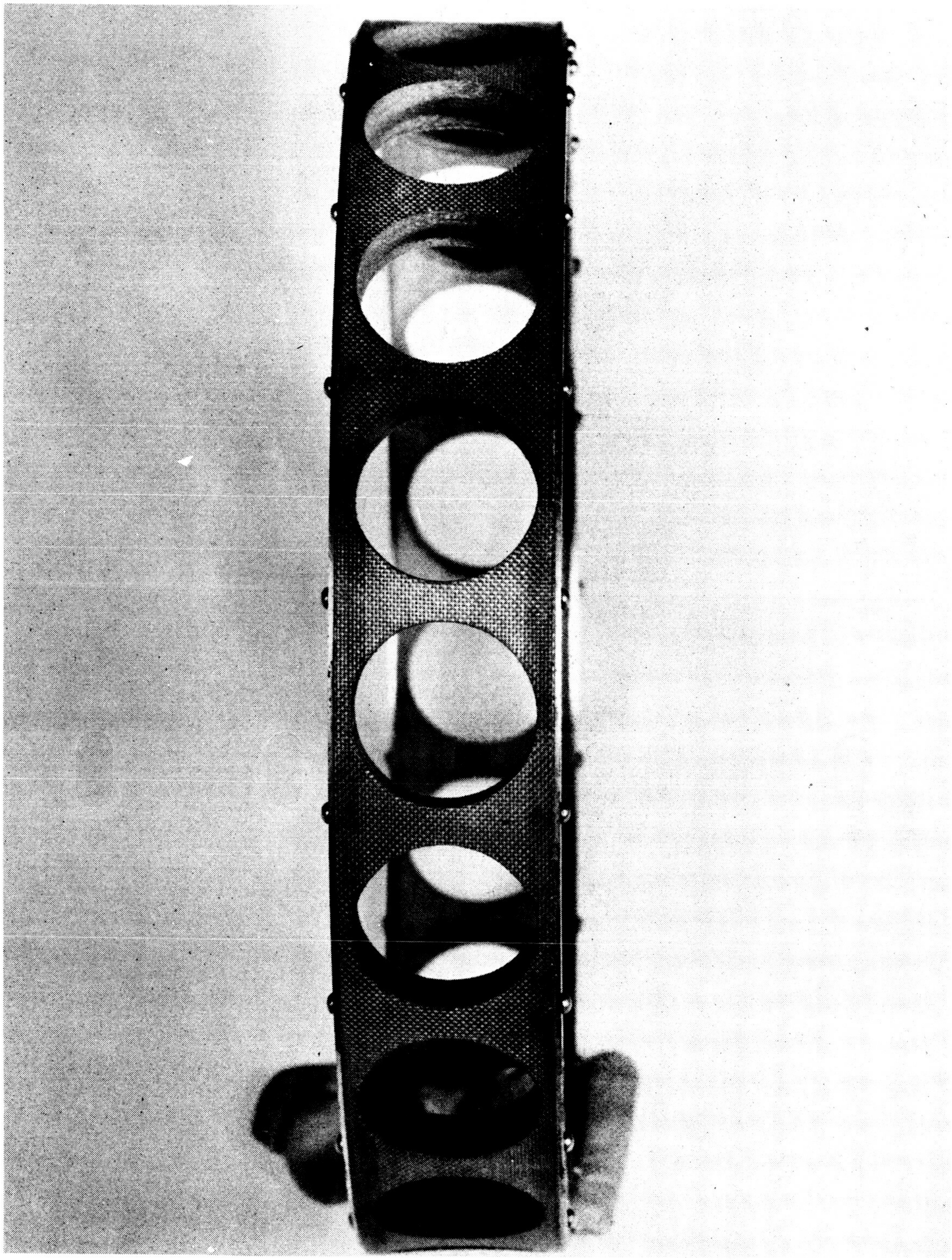

Figure 33

Thrust Bearing, Cage (S/N 52A)

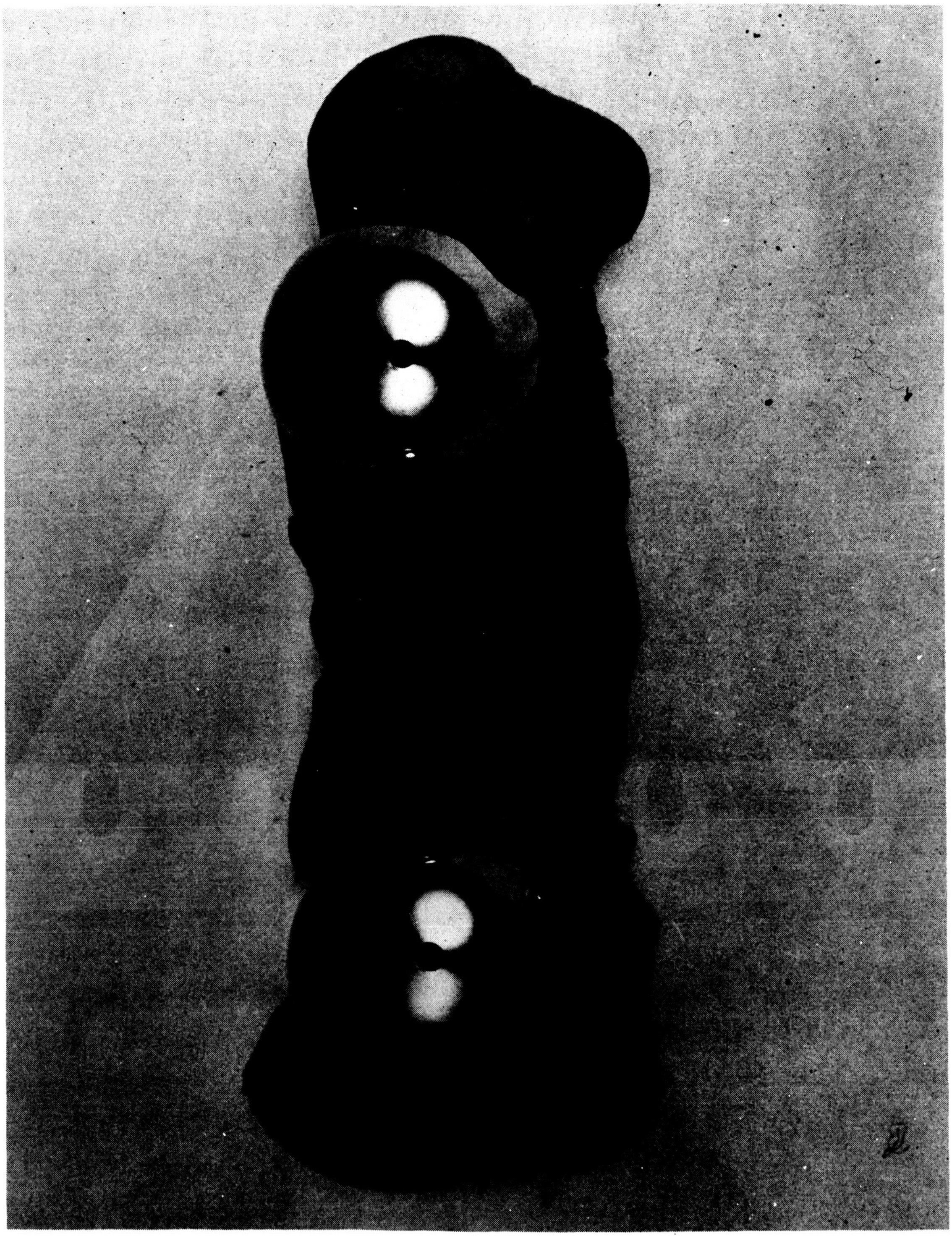

Figure 34

Thrust Bearing, Balls (S/N 52B)

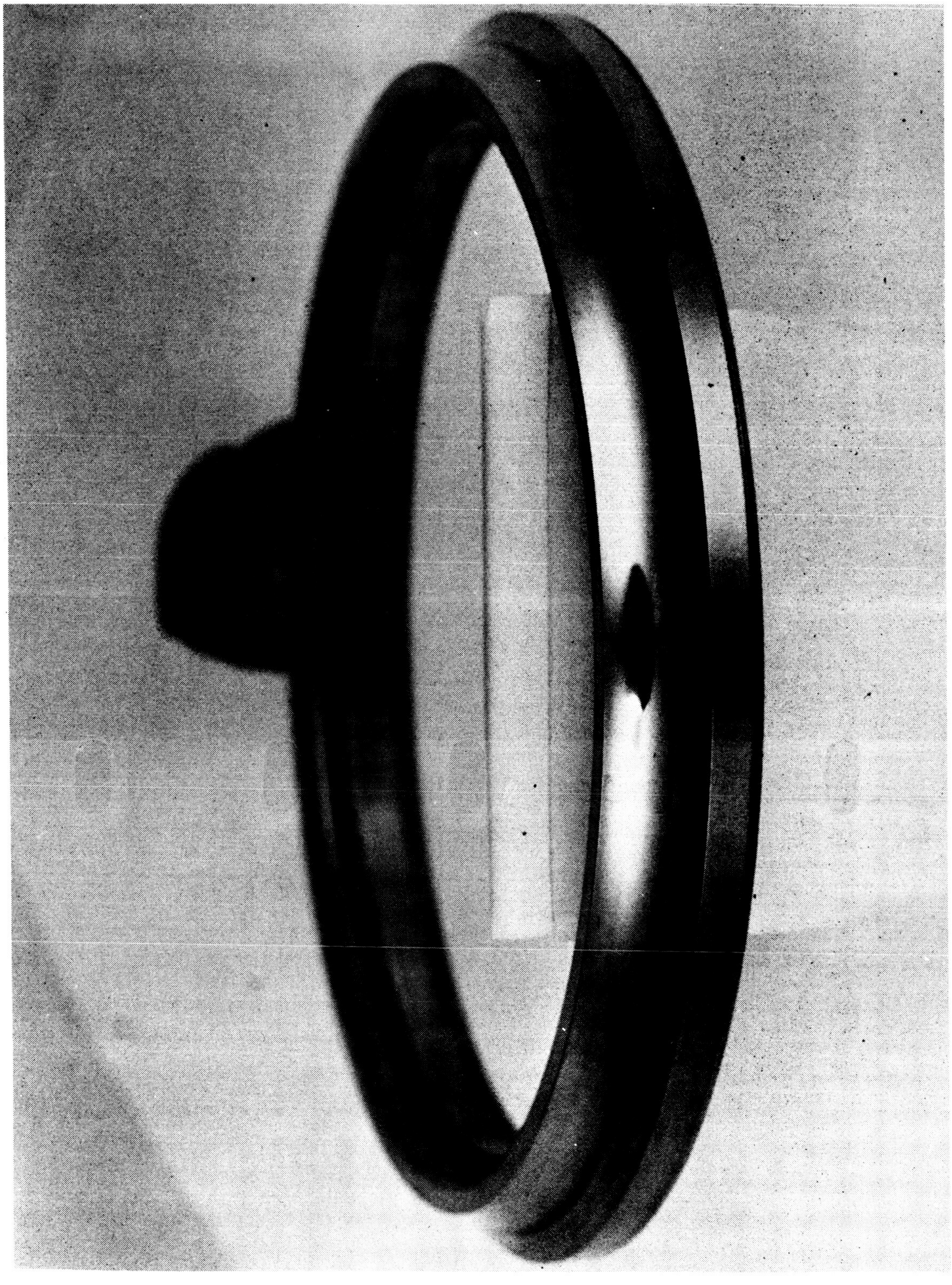

Figure 35

Thrust Bearing, Inner Race (S/N 52B)

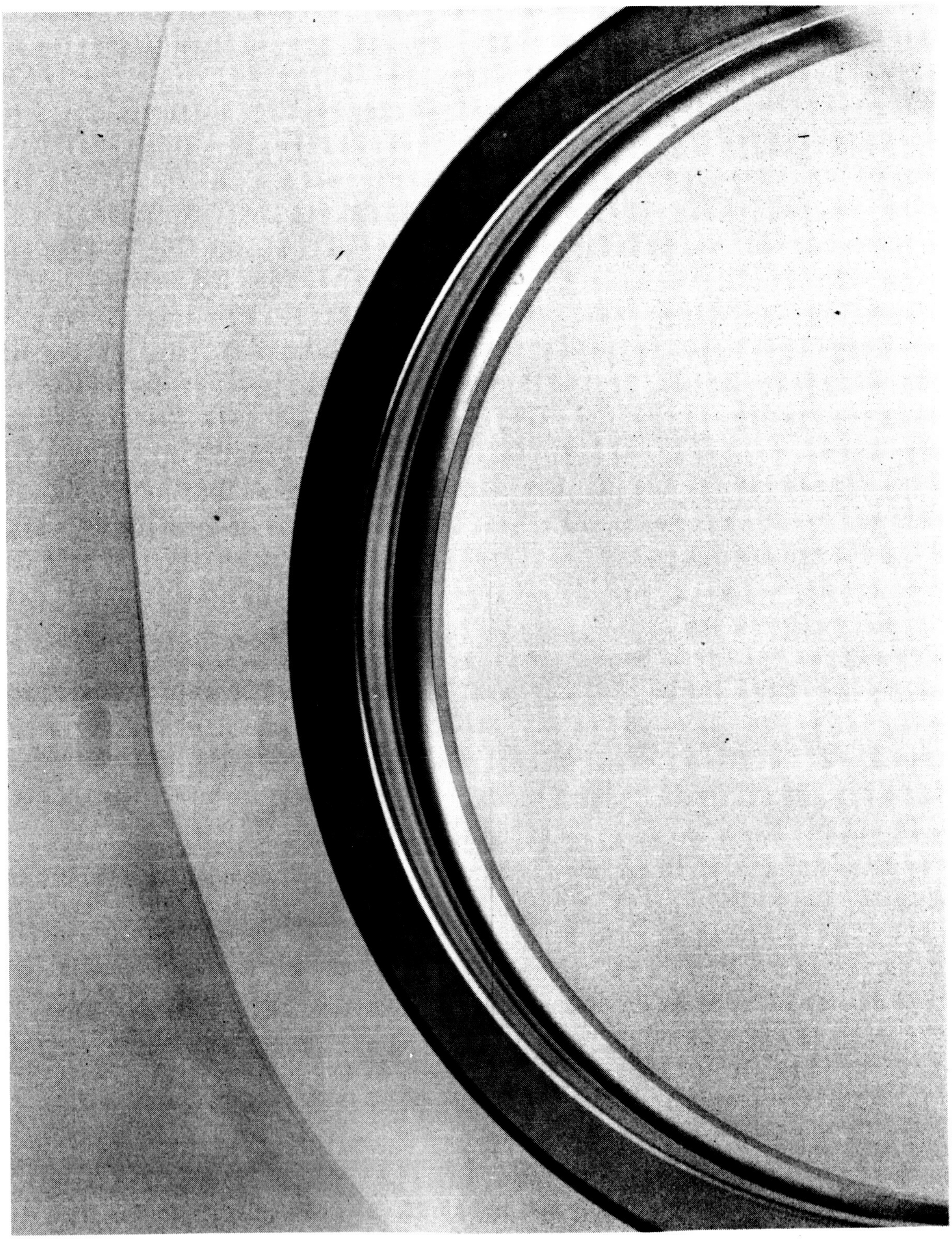

Figure 36

Thrust Bearing, Outer Race (S/N 52B)

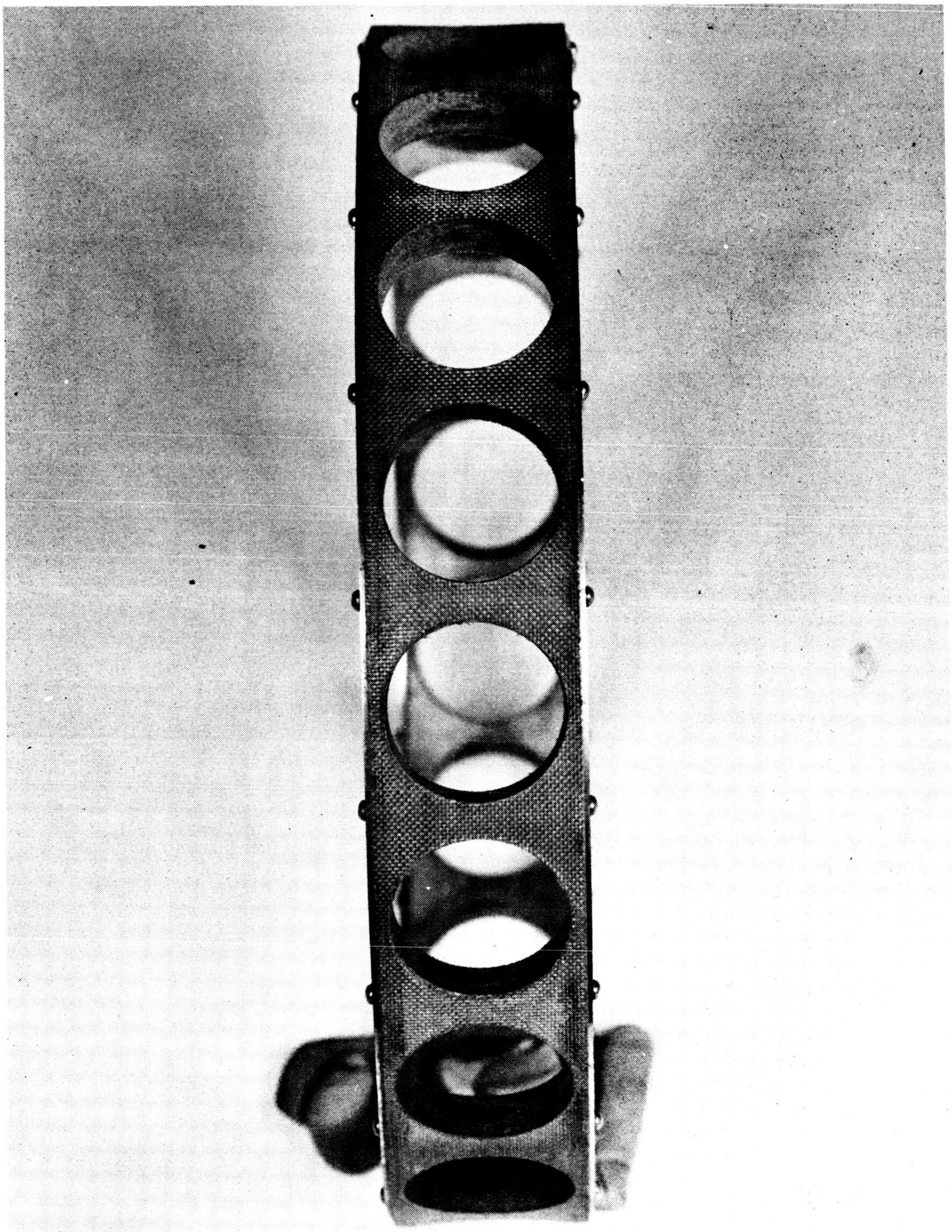

Figure 37

Thrust Bearing, Cage (S/N 52B)

(b) Discussion

Both roller bearings were in excellent condition at the conclusion of the tests. The tandem thrust bearings showed some heat discoloration, but dimensional inspection of ball size and ball size variation showed that the bearings were reuseable because no measurable dimensional changes had occurred. The discoloration was identical to that noted in the bearings used in the peripheral evaluation phase, demonstrating the direct applicability of the component test results to the turbopump. Some load sharing in the reverse direction, perhaps as high as 80%/20%, was observed. Accurate determination was impossible because of the wide wear track resulting from the various load conditions.

(2) Category B - High Load, High Acceleration, Turbopump (See Figures 1 and 2)

(a) Summary

Total Tests	14
Total Duration Accrued (Sec)	148
Total Failures	0
Typical Thrust Load (Lb)	25,000/40,000
Maximum Thrust Load (Lb)	67,000
Duration at Maximum Load (Sec)	5

(b) Discussion

All bearings were in excellent condition at the conclusion of the tests. The input (turbine) end roller bearing showed evidence of some solid contaminants having passed through the bearing without damaging it. Again, the ball thrust bearings showed the wide wear track characteristics of varied load operation, which made accurate determination of load sharing impossible. Examination of the highest load wear track indicates that load sharing was at least as high as 60%/40% with the bearing closest to the pump being the most highly loaded. The output (pump) end roller bearing showed no evidence of any damage. The lack of discoloration on the armalon separator ball pockets indicates that both quantity and distribution of the coolant was adequate.

IV. CONCLUSIONS

The system of bearings developed during the program meets all of the turbopump requirements at the current state of development. In addition, it has been proved that bearing loads of at least 100% of the design values can be sustained for durations of at least 5000 sec.

The results of peripheral tests conducted in preparation for turbopump testing showed that operation is possible at bearing housing internal pressures that are considerably lower than 450 psia. The reduction of these pressures to a sufficient margin above vapor pressure to prevent local boiling and to a level compatible with the pump backvane cavity, to which the coolant is returned, eases the turbine end dynamic seal problem in proportion to the pressure-level reduction.

V. RECOMMENDATIONS

The next logical step toward an operational engine system would be an expansion of the turbopump testing to extended-duration tests at full-power levels to verify the life capability of the bearings in the operational environment. No problems with the bearings are foreseen in extended-duration tests. Although the longer tests are unquestionably more severe, the knowledge of pump and turbine performance gained during these turbopump tests would allow very accurate thrust balancing.

Substantial cost savings for bearings required for subsequent turbopump and engine development are possible by easing tolerances (ball size and variation, sphericity, race curvature) and design requirements. At this stage of development, the ability to predict thrust and reasonably control its affecting parameters allows operation with less probability of unexpected thrust excursion. Bearing component qualification testing would be required prior to turbopump use.

An optimization of the coolant flow rates seems appropriate when considering the turbopump efficiency penalty of recirculating flow. Such potential flow-rate reduction requires confirmation under extended-duration service.

Simplification of the entire coolant circuit seems feasible because the bearing performance does not appear overly sensitive to flow rates. In particular, this simplification could be comprised of the replacement of the triple-path measuring venturi with a single flow-rate monitor (e.g., a simple orifice differential pressure) and the elimination of the jet rings with their associated tight tolerances, and reverse orientation and clogging potential.

BIBLIOGRAPHY

1. Carney, J. A., Post-Test Analysis of M-1 LO_2 TPA Tandem Ball Bearings P/N 281642, S/N 18 and 32, Report RMR 0192, Aerojet-General, 27 Mar 1964.

2. Carney, J. A., Post-Test Analysis of M-1 LO_2 TPA Bearings P/N 288140, (S/N 428 and 429 Test #1.2-05-EHW-001 thru 018), Report 0177, Aerojet-General, 19 Feb 1964.

3. Dubief, J., Heat Generation in Annular Contact Ball Bearings Under Axial Load, Report RMR 0075, Aerojet-General, 16 Jan 1963.

4. Kuczynski, A., Analysis of LOX - TPA Bearings, Report DVR 64-410, Aerojet-General, 1 Sep 1964.

5. Kuczynski, A., Post-Test Analysis of M-1 LO_2 Ball Bearings P/N 281642 Used on Test #5006, Report RMR 0208, Aerojet-General, 26 May 1964.

6. Kuczynski, A., Post-Test Analysis of M-1 LO_2 TPA Bearings P/N 288280 Used in Test No. 1362 - 004, Report RMR 0178, Aerojet-General, 19 Feb 1964.

APPENDIX A

BEARING CALIBRATION WORKSHEETS

(PRE-TEST)

BEARING CALIBRATION WORKSHEET

APPENDIX A

TYPE Ball MFR. ND P/N 281642 S/N 0000031A DATE CALIBRATED 2-28-64

TECHNICIAN Don Heath

CHECK BOX FOR DESIRED MEASUREMENT

	Assembly Dimensions		Acutal
X	Bore Diameter	(1)	4.330390
		(1)90°	4.330310
	For Split Inner Race Ball Brg.	(2)	4.330390
		(2)90°	4.330350
X	Outer Diameter		6.692570
		90°	6.692430
X	Width	Inner	1.6019
		Outer	1.1019
X	Radial Clearance		.0037
	Gage Load		--
X	End Play		.0195
	Gage Load		--
X	Diametral Cage Clearance	Inner	5.842
		Outer	5.828
X	Cage Pocket Clearance	Diametral	.034
		End (Rollers)	
X	Inner Groove Run-Out With Reference Side (Ball Bearings)	(1)	.000050
		(2)	.000050
X	Width Variation	Inner	.000010
		Outer	.000030
X	Outer Groove Run-Out With Reference Side (Ball Bearings)	(1)	.000090
		(2)	--
NO	Radius of Raceway Curvature (Ball Brg)	Inner	--
		Outer	--
X	Inner Ring Radial Run-Out	(1)	.000040
		(2)	.000051
X	Outer Ring Radial Run-Out		
X	⊥ of Bore to Side of Inner Ring	(1)	.000000
		(2)	.000060
X	⊥ of O.D. to Side of Outer Ring	(1)	
		(2)	
X	Land Diameters	Inner	
		Outer	

X Rolling Element Diameter Variation

	Off Wear Path (or New Brg)	Wear Path		Off Wear Path (or New Brg)	Wear Path
1.	0		15.	+ 7	
2.	-14		16.	+ 5	
3.	0		17.	-15	
4.	+ 7		18.	- 9	
5.	+13		19.	-12	
6.	+ 4		20.		
7.	-12		21.		
8.	-13		22.		
9.	-10		23.		
10.	+ 2		24.		
11.	+14		25.		
12.	-19		26.		
13.	- 5		27.		
14.	+10		28.		

Max. Wear

Max. Variation .000033

Comments on Visual Examination and Remarks

BEARING CALIBRATION WORKSHEET

TYPE Ball MFR. ND P/N 281642 S/N 0000031B DATE CALIBRATED 2-28-64

TECHNICIAN Don Heath

CHECK BOX FOR DESIRED MEASUREMENT

	Assembly Dimensions		Acutal
X	Bore Diameter	(1)	4.330450
		(1)90°	4.330290
	For Split Inner Race Ball Brg.	(2)	4.330400
		(2)90°	4.330495
X	Outer Diameter		6.692590
		90°	6.692530
X	Width	Inner	1.6019
		Outer	1.1019
X	Radial Clearance		.004
	Gage Load		--
X	End Play		.019
	Gage Load		--
X	Diametral Cage Clearance	Inner	5.828
		Outer	5.842
X	Cage Pocket Clearance	Diametral	.033
		End (Rollers)	
X	Inner Groove Run-Out With Reference Side (Ball Bearings)	(1)	.0001
		(2)	.000125
X	Width Variation	Inner	.000030
		Outer	.000060
X	Outer Groove Run-Out With Reference Side (Ball Bearings)	(1)	.000130
		(2)	--
NO	Radius of Raceway Curvature (Ball Brg)	Inner	--
		Outer	--
X	Inner Ring Radial Run-Out	(1)	.000050
		(2)	.000065
X	Outer Ring Radial Run-Out		
X	⊥ of Bore to Side of Inner Ring	(1)	.000010
		(2)	.000020
X	⊥ of O.D. to Side of Outer Ring	(1)	.000040
		(2)	--
X	Land Diameters	Inner	--
		Outer	-- 5.842

X Rolling Element Diameter Variation

	Off Wear Path (or New Brg)	Wear Path		Off Wear Path (or New Brg)	Wear Path
1.	0		15.	+12	
2.	+ 8		16.	+21	
3.	+16		17.	+16	
4.	+12		18.	+18	
5.	+25		19.	+17	
6.	0		20.		
7.	+23		21.		
8.	0		22.		
9.	+18		23.		
10.	+29		24.		
11.	+16		25.		
12.	+14		26.		
13.	+17		27.		
14.	+20		28.		

Max. Wear

Max. Variation .000029

Comments on Visual Examination and Remarks

BEARING CALIBRATION WORKSHEET

TYPE Ball MFR. ND P/N 281642 S/N 0000032A DATE CALIBRATED 2-3-64

TECHNICIAN Don Heath

CHECK BOX FOR DESIRED MEASUREMENT

Check	Assembly Dimensions		Acutal
X	Bore Diameter	(1)	4.330300
		(1)90°	4.330345
	For Split Inner Race Ball Brg.	(2)	4.330450
		(2)90°	4.330435
X	Outer Diameter		6.692630
		90°	6.692400
X	Width	Inner	1.6020
		Outer	1.1019
X	Radial Clearance		.0036
	Gage Load		
X	End Play		.0190
	Gage Load		
X	Diametral Cage Clearance	Inner	5.842
		Outer	5.829
X	Cage Pocket Clearance	Diametral	.034
		End (Rollers)	
X	Inner Groove Run-Out With Reference Side (Ball Bearings)	(1)	.0001
		(2)	.000125
X	Width Variation	Inner	.000170
		Outer	.000020
X	Outer Groove Run-Out With Reference Side (Ball Bearings)	(1)	.00005
		(2)	
NO	Radius of Raceway Curvature (Ball Brg)	Inner	
		Outer	
X	Inner Ring Radial Run-Out	(1)	.0001
		(2)	.00005
X	Outer Ring Radial Run-Out		
X	⊥ of Bore to Side of Inner Ring	(1)	.000010
		(2)	.000050
X	⊥ of O.D. to Side of Outer Ring	(1)	.000000
		(2)	
X	Land Diameters	Inner	
		Outer	

[X] Rolling Element Diameter Variation

	Off Wear Path (or New Brg)	Wear Path		Off Wear Path (or New Brg)	Wear Path
1.	0		15.	+17	
2.	+28		16.	+ 6	
3.	+ 8		17.	+14	
4.	+19		18.	+18	
5.	+21		19.	-11	
6.	+14		20.		
7.	+16		21.		
8.	+26		22.		
9.	+21		23.		
10.	+16		24.		
11.	+ 4		25.		
12.	+ 2		26.		
13.	+17		27.		
14.	- 5		28.		

Max. Wear

Max. Variation .000039

Comments on Visual Examination and Remarks

Contact Angle = 20°

C/A Remeasure = 22.75° By 5-3-64

BEARING CALIBRATION WORKSHEET

TYPE Ball MFR. ND P/N 281642 S/N 0000032B DATE CALIBRATED 2-3-64

TECHNICIAN Don Heath

CHECK BOX FOR DESIRED MEASUREMENT

	Assembly Dimensions		Acutal
[X]	Bore Diameter	(1)	4.330505
		(1)90°	4.330335
	For Split Inner Race Ball Brg.	(2)	4.330360
		(2)90°	4.330440
[X]	Outer Diameter		6.692550
		90°	6.692620
[X]	Width	Inner	1.5996
		Outer	1.0995
[X]	Radial Clearance		.0033
	Gage Load		
[X]	End Play		.0184
	Gage Load		
[X]	Diametral Cage Clearance	Inner	5.842
		Outer	5.829
[X]	Cage Pocket Clearance	Diametral	.033
		End (Rollers)	
[X]	Inner Groove Run-Out With Reference Side (Ball Bearings)	N (1)	.0001
		LU (2)	.00006
[X]	Width Variation	Inner	.000075
		Outer	.000040
[X]	Outer Groove Run-Out With Reference Side (Ball Bearings)	(1)	.000075
		(2)	
[NO]	Radius of Raceway Curvature (Ball Brg)	Inner	
		Outer	
[X]	Inner Ring Radial Run-Out	(1)	.0004
			.00005
[X]	Outer Ring Radial Run-Out	(2)	.0002
[X]	⊥ of Bore to Side of Inner Ring	(1)	.000010
		(2)	.000050
[X]	⊥ of O.D. to Side of Outer Ring	(1)	.000000
		(2)	
[X]	Land Diameters	Inner	
		Outer	

[X] Rolling Element Diameter Variation

	Off Wear Path (or New Brg)	Wear Path		Off Wear Path (or New Brg)	Wear Path
1.	0		15.	- 7	
2.	+10		16.	+ 4	
3.	+ 3		17.	+ 6	
4.	+16		18.	- 7	
5.	+ 7		19.	+14	
6.	+10		20.		
7.	+ 6		21.		
8.	+18		22.		
9.	+ 5		23.		
10.	+20		24.		
11.	- 4		25.		
12.	+ 6		26.		
13.	+34		27.		
14.	+15		28.		

Max. Wear

Max. Variation .000041

Comments on Visual Examination and Remarks

Contact Angle = 21.5°

C/A Remeasure = 22.75° By 5-3-64

APPENDIX B

BEARING CALIBRATION WORKSHEETS

(POST-TEST)

BEARING CALIBRATION WORKSHEET

APPENDIX B

TYPE Ball MFR. ______ P/N 281642 S/N 31A DATE CALIBRATED 6-17-64

TECHNICIAN S. Wilson

CHECK BOX FOR DESIRED MEASUREMENT

	Assembly Dimensions		Acutal
☐	Bore Diameter Large	(1)	4.33049
		(1)90°	4.33043
	For Split Small	(2)	4.33045
	Inner Race Ball Brg.	(2)90°	4.33038
☐	Outer Diameter		6.69265
		90°	6.69261
☐	Width	Inner	1.6018
		Outer	1.1019
☐	Radial Clearance		.0035
	Gage Load		5 lb
☐	End Play		.0193
	Gage Load		N/A
☐	Diametral Cage Clearance	Inner	.164
		Outer	.014
☐	Cage Pocket Clearance	Diametral	.059
		End (Rollers)	N/A
☐	Inner Groove Run-Out With Reference Side (Ball Bearings)	Small (1)	.000125
		Large (2)	.000075
☐	Width Variation	Inner	.00006
		Outer	.00005
☐	Outer Groove Run-Out With Reference Side (Ball Bearings)	(1)	.000075
		(2)	N/A
☐	Radius of Raceway Curvature (Ball Brg)	Inner	N/A
		Outer	N/A
☐	Inner Ring Radial Run-Out	Small (1)	.000075
		Large (2)	.0001
☐	Outer Ring Radial Run-Out →		.000125
☐	⊥ of Bore to Side of Inner Ring	(1)	.00003
		Large (2)	.00003
☐	⊥ of O.D. to Side of Outer Ring	Small (1)	.000020
		(2)	
☐	Land Diameters	Inner	5.190
		Outer	5.843

☐ Rolling Element Diameter Variation

	Off Wear Path (or New Brg)	Wear Path		Off Wear Path (or New Brg)	Wear Path
1.		0	15.		+100
2.		-40	16.		-100
3.		+125	17.		- 5
4.		-60	18.		- 75
5.		-10	19.		- 25
6.		-60	20.		
7.		-70	21.		
8.		+75	22.		
9.		+45	23.		
10.		-50	24.		
11.		+80	25.		
12.		+70	26.		
13.		+35	27.		
14.		-50	28.		

Max. Wear ______

Max. Variation .000225

Comments on Visual Examination and Remarks

BEARING CALIBRATION WORKSHEET

TYPE Ball MFR. ______ P/N 281642 S/N 31B DATE CALIBRATED 6-17-64

TECHNICIAN S. Wilson

CHECK BOX FOR DESIRED MEASUREMENT

Assembly Dimensions		Acutal
Bore Diameter Large	(1)	4.33046
	(1)90°	4.33054
For Split Small Inner Race Ball Brg.	(2)	4.33044
	(2)90°	4.33049
Outer Diameter		6.69257
	90°	6.69263
Width	Inner	1.6019
	Outer	1.1019
Radial Clearance		.0032
Gage Load		5 lbs
End Play		.0195
Gage Load		N/A
Diametral Cage Clearance	Inner	.164
	Outer	.016
Cage Pocket Clearance	Diametral	.058
	End (Rollers)	N/A
Inner Groove Run-Out With Reference Side (Ball Bearings)	Small(1)	.000125
	Large(2)	.000125
Width Variation	Inner	.00015
	Outer	.00006
Outer Groove Run-Out With Reference Side (Ball Bearings)	(1)	.00005
	(2)	N/A
Radius of Raceway Curvature (Ball Brg)	Inner	N/A
	Outer	N/A
Inner Ring Radial Run-Out	Small (1)	.000075
	Large (2)	.000075
Outer Ring Radial Run-Out	→	.000125
⊥ of Bore to Side of Inner Ring	Large (1)	.00002
	Small (2)	.00001
⊥ of O.D. to Side of Outer Ring	(1)	.00001
	(2)	N/A
Land Diameters	Inner	-5.190
	Outer	5.843

Rolling Element Diameter Variation

	Off Wear Path (or New Brg)	Wear Path		Off Wear Path (or New Brg)	Wear Path
1.		0	15.		-10
2.		-17	16.		+10
3.		+155	17.		+130
4.		0	18.		- 5
5.		+10	19.		+50
6.		+30	20.		
7.		- 5	21.		
8.		+10	22.		
9.		-10	23.		
10.		+50	24.		
11.		- 5	25.		
12.		+ 5	26.		
13.		+170	27.		
14.		+40	28.		

Max. Wear ______

Max. Variation .000187

Comments on Visual Examination and Remarks

BEARING CALIBRATION WORKSHEET

TYPE Ball MFR. ______ P/N 281642 S/N 32A DATE CALIBRATED 6-17-64

TECHNICIAN S. Wilson

CHECK BOX FOR DESIRED MEASUREMENT

	Assembly Dimensions		Acutal
☐	Bore Diameter	Large (1)	4.33054
		(1)90°	4.33056
	For Split Inner Race Ball Brg.	Small (2)	4.33054
		(2)90°	4.33069
☐	Outer Diameter		6.69264
		90°	6.69261
☐	Width	Inner	1.6021
		Outer	1.1021
☐	Radial Clearance		.008
	Gage Load		N/A
☐	End Play		.029
	Gage Load		N/A
☐	Diametral Cage Clearance	Inner	.165
		Outer	.017
☐	Cage Pocket Clearance	Diametral	.058
		End (Rollers)	N/A
☐	Inner Groove Run-Out With Reference Side (Ball Bearings)	Small(1)	.00015
		Large(2)	.00015
☐	Width Variation	Inner	.00008
		Outer	.00005
☐	Outer Groove Run-Out With Reference Side (Ball Bearings)	(1)	.000125
		(2)	N/A
☐	Radius of Raceway Curvature (Ball Brg)	Inner	N/A
		Outer	N/A
☐	Inner Ring Radial Run-Out	Small (1)	.000125
		Large (2)	.00005
☐	Outer Ring Radial Run-Out	→	.000175
☐	⊥ of Bore to Side of Inner Ring	Large(1)	.00005
		Small(2)	.00007
☐	⊥ of O.D. to Side of Outer Ring	(1)	.00002
		(2)	N/A
☐	Land Diameters	Inner	5.190
		Outer	5.844

* ☐ Rolling Element Diameter Variation

	Off Wear Path (or New Brg)	Wear Path		Off Wear Path (or New Brg)	Wear Path
1.		0	15.		-250
2.		-200	16.		-130
3.		-180	17.		-470
4.		-310	18.		- 80
5.		-240	19.		-180
6.		-220	20.		
7.		-170	21.		
8.		-120	22.		
9.		-500	23.		
10.		-250	24.		
11.		-100	25.		
12.		+ 10	26.		
13.		-300	27.		
14.		-320	28.		

Max. Wear .000510

Max. Variation ______

Comments on Visual Examination and Remarks

* Balls out of Round up to .0005

BEARING CALIBRATION WORKSHEET

TYPE Ball MFR. ________ P/N 281642 S/N 32B DATE CALIBRATED 6-17-64
TECHNICIAN S. Wilson

CHECK BOX FOR DESIRED MEASUREMENT

Assembly Dimensions		Acutal
☐ Bore Diameter	Large (1)	4.3305
	(1)90°	4.33055
For Split Inner Race Ball Brg.	Small (2)	4.33067
	(2)90°	4.33052
☐ Outer Diameter		6.69264
	90°	6.69266
☐ Width	Inner	1.5997
	Outer	.9997
☐ Radial Clearance		.0078
Gage Load		N/A
☐ End Play		.029
Gage Load		N/A
☐ Diametral Cage Clearance	Inner	.165
	Outer	.014
☐ Cage Pocket Clearance	Diametral	.060
	End (Rollers)	N/A
☐ Inner Groove Run-Out With Reference Side (Ball Bearings)	Small(1)	.00015
	Large(2)	.000075
☐ Width Variation	Inner	.00007
	Outer	.00004
☐ Outer Groove Run-Out With Reference Side (Ball Bearings)	(1)	.000075
	(2)	N/A
☐ Radius of Raceway Curvature (Ball Brg)	Inner	N/A
	Outer	N/A
☐ Inner Ring Radial Run-Out	Small (1)	.00015
	Large (2)	.00005
☐ Outer Ring Radial Run-Out		.00015
☐ ⊥ of Bore to Side of Inner Ring	Large(1)	.00001
	Small(2)	.00045
☐ ⊥ of O.D. to Side of Outer Ring	(1)	.00003
	(2)	
☐ Land Diameters	Inner	5.190
	Outer	5.844

* ☐ Rolling Element Diameter Variation

	Off Wear Path (or New Brg)	Wear Path		Off Wear Path (or New Brg)	Wear Path
1.		0	15.		-760
2.		-400	16.		-600
3.		-440	17.		-780
4.		-340	18.	**over	-.001
5.		-110	19.	**over	-.001
6.		-300	20.		
7.		+ 50	21.		
8.		-100	22.		
9.		-130	23.		
10.		-350	24.		
11.		-450	25.		
12.		- 80	26.		
13.		-610	27.		
14.		-320	28.		

Max. Wear ________

Max. Variation .00105? see note

Comments on Visual Examination and Remarks

*Balls out of round up to .0005

**Note: Two balls out of range of machine (Mibus). Unable to measure.

APPENDIX C

BEARING TEST RESULTS SUMMARY

APPENDIX C

BEARING TEST RESULTS SUMMARY

PHASE I - PRELIMINARY EVALUATION

CATEGORY A - SINGLE THRUST BEARING, CONSTANT SPEED

TURBINE DRIVEN TESTER (FIGURES 3 AND 4)

BUILDUP NO.	NO. OF TESTS	PART NO.	SHAFT SPEED RPM	THRUST LOAD LBS	TOTAL DURATION SEC	COOLANT FLUID	COOLANT FLOW RATE GPM/BRG	COOLANT PRESS PSIG	CONFIGURATION DESCRIPTION	RESULTS
1	1	EX31000C	4000	10,200	412	LO_2	12	103	New Bearing	Reuseable
	1	EX31000C	4000	20,000	412	LO_2	12	103	New Bearing	Reuseable
2	1	EX31000C	4000	20,000	238	LO_2	5.5	130	Used In Buildup #1	Burned Races and Balls
	1	EX31000C	4000	10,200	238	LO_2	5.5	130	Used in Buildup #1	Reuseable
3	3	EX31000C	4000	25,000	232	LO_2	7.5	120	New Bearing	Reuseable
	3	EX31000C	4000	12,000	232	LO_2	7.5	120	New Bearing	Reuseable
4	3	EX31000C	4500	33,000	469	LO_2	25	300	Used in Buildup #3	Reuseable
	3	EX31000C	4500	17,500	469	LO_2	25	300	Used in Buildup #3	Reuseable
5	1	288280	4000	28,650	100	LO_2	20	300	New Bearing Half of Tandem Set	Reuseable
	1	288280	4000	12,850	100	LO_2	20	300	New Bearing Half of Tandem Set	Reuseable
6	3	288140	4000	30,000	370	LO_2	20	300	New Bearing	Reuseable
	3	288140	4000	11,500	370	LO_2	20	300	New Bearing	Pitted Races, Evidence of Ball Skidding Reuseable
7	1	288140	4000	30,000	20	LO_2	21	300	New Bearing - Modified Cage for Improved Coolant Flow	Reuseable
	1	288140	4000	11,500	20	LO_2	21	300	New Bearing - Modified Cage for Improved Coolant Flow	Reuseable
8	3	288140	4000	31,000	770	LO_2	19		Used in Buildup #7	Reuseable
	3	288140	4000	12,000	770	LO_2	19		Used in Buildup #7	Reuseable
9	4	288140	4000	23,000	2664	LO_2	20		Used in Buildup #8	Reuseable
	4	288140	4000	4,000	2664	LO_2	20		Used in Buildup #8	Reuseable - Distress on Balls and Races

BEARING TEST RESULTS SUMMARY

PHASE I - PRELIMINARY EVALUATION

CATEGORY B - SINGLE RADIAL BEARING, CONSTANT SPEED - MOTOR DRIVEN TESTER (FIGURES 8 AND 10)

BUILDUP NO.	NO. OF TESTS	PART NO.	SHAFT SPEED RPM	RADIAL LOAD LBS	TOTAL DURATION SEC	COOLANT FLUID	COOLANT FLOW RATE GPM/BRG	COOLANT PRESS PSIG	CONFIGURATION DESCRIPTION	RESULTS
1	3	281644	4000	8850	234	LO_2	14	340	New Bearing	Reuseable
	3	281644	4000	8850	234	LO_2	14	340	New Bearing	Reuseable
	3	281644	4000	8850	234	LO_2	14	340	New Bearing	Reuseable
	3	281644	4000	8850	234	LO_2	14	340	New Bearing	Reuseable

BEARING TEST RESULTS SUMMARY

PHASE I - PRELIMINARY EVALUATION

CATEGORY C - SINGLE THRUST & RADIAL BEARING, ACCELERATION CAPABILITIES - TURBINE DRIVEN ACCELERATION TESTER (FIGURES 5 AND 6)

BUILDUP NO.	NO. TESTS	PART NO.	SHAFT SPEED RPM	ACCEL. RPM PER SEC	LOADS LBS	TOTAL DURATION SEC	COOLANT FLUID	COOLANT FLOW RATE GPM/BRG	COOLANT PRESS PSIG	CONFIGURATION DESCRIPTION	RESULTS
1	1	EX31000C	5500	-	4400	510	LO_2	6	147	New Bearing	Reuseable
		SUBSTITUTE ROLLER BEARING USED									
2	1	EX31000C	4000	-	2000	200	LO_2	10.5	97	New Bearing	Reuseable
		SUBSTITUTE ROLLER BEARING USED									
3	1	EX31000C	4000	-	6650	178	LO_2	16.5	300	Previously Tested in Single Brg. Tests, 675 sec	Reuseable
	1	281644	4000	-	2240	178	LO_2	2.5	300	New Bearing	Reuseable
4	3	EX31000C	6000	1600	6650	239	LO_2	18.5	300	Used in Buildup #3	Reuseable
	3	281644	6000	1600	2280	239	LO_2	6.5	300	Used in Buildup #3	Reuseable
5	3	288140	4000	2000	4500	94	LO_2	9	300	New Bearing	Reuseable
	3	281644	4000	2000	2250	94	LO_2	3	300	New Bearing	Reuseable
6	14	288280	4000	8000	5200	28	LO_2	10.5	295	New Bearing	Reuseable
	14	281644	4000	8000	500	28	LO_2	3.5	295	Used in Buildup #5	Reuseable
7	10	281642	4000	8000	5000	27	LO_2	10.5	300	New Bearing	Reuseable
	10	281644	4000	8000	540	27	LO_2	3.5	300	Used in Buildup #4	Reuseable

BEARING TEST RESULTS SUMMARY

PHASE I - PRELIMINARY EVALUATION

CATEGORY D - SINGLE THRUST & RADIAL BEARINGS, PTA TESTER (FIGURES 11 AND 12)

BUILDUP NO.	NO. OF TESTS	PART NO.	SHAFT SPEED RPM	THRUST RADIAL LOAD LBS	TOTAL DURATION SEC	COOLANT FLUID	COOLANT FLOW RATE GPM/BRG	COOLANT PRESS PSIG	CONFIGURATION DESCRIPTION	RESULTS
1	9	EX31000C	2000	6700	146	LN_2	8.5	450	New Bearing	
	9	281643	2000	2000	146	LN_2	2.75	450	New Bearing	
	9	281644	2000	6000	146	LN_2	2.75	450	New Bearing	
1	1	EX31000C	2000	6670	12	LN_2	7.2	400		
	1	281643	2000	2000	12	LN_2	2.3	400		
	1	281644	2000	6000	12	LN_2	2.3	400		
1	1	EX31000C	2000	6670	18	LN_2	7.2	300		
	1	281643	2000	2000	18	LN_2	2.3	300		
	1	281644	2000	6000	18	LN_2	2.3	300		
1	1	EX31000C	2000	6670	46	LN_2	5.66	200		
	1	281643	2000	2000	46	LN_2	1.83	200		
	1	281644	2000	6000	46	LN_2	1.83	200		
1	1	EX31000C	2000	6670	790	LN_2	3.4	110		
	1	281643	2000	2000	790	LN_2	1.1	110		
	1	281644	2000	6000	790	LN_2	1.1	110		
1	2	EX31000C	2000	6670	290	LN_2	5.3	490		Test Parameters OK
	2	281643	2000	2000	290	LN_2	1.7	490		
	2	281644	2000	6000	290	LN_2	1.7	490		

CATEGORY D - SINGLE THRUST & RADIAL BEARINGS, PTA TESTER (FIGURES 11 AND 12)

BUILDUP NO.	NO. OF TESTS	PART NO.	SHAFT SPEED RPM	THRUST RADIAL LOAD LBS	TOTAL DURATION SEC	COOLANT FLUID	COOLANT FLOW RATE GPM/BRG	COOLANT PRESS PSIG	CONFIGURATION DESCRIPTION	RESULTS
1	1	EX31000C	4000	16,550	100	LN_2	11.0	270		
1	1	281643	4000	2,650	100	LN_2	3.6	270		
1	1	281644	4000	7,500	100	LN_2	3.6	270		
1	1	EX31000C	2000	16,550	210	LN_2	11.0	130		
1	1	281643	2000	2,650	210	LN_2	3.6	130		
1	1	281644	2000	7,500	210	LN_2	3.6	130		
1	1	EX31000C	2000	8,150	30	LN_2	12.5	280		
1	1	281643	2000	1,325	30	LN_2	3.75	280		
1	1	281644	2000	3,750	30	LN_2	3.75	280		
1	2	EX31000C	4000	24,800	45	LN_2	12.5	280		
1	2	281643	4000	4,000	45	LN_2	3.75	280		
1	2	281644	4000	12,000	45	LN_2	3.75	280		
1	1	EX31000C	2000	8,000	30	LN_2	10.5	400		
1	1	281643	2000	1,325	30	LN_2	3.5	400		
1	1	281644	2000	3,500	30	LN_2	3.5	400		
1	3	EX31000C	4000	17,000	52	LN_2	10.5	400		2 Bearings Reuseable 2 Bearings Chipped Races
1	3	281643	4000	250	52	LN_2	3.5	400		Bearings Reuseable
1	3	281644	4000	7,500	52	LN_2	3.5	400		Bearings Reuseable

BEARING TEST RESULTS SUMMARY

PHASE II - QUALIFICATION OF PREFERRED CONFIGURATION FOR TURBOPUMP OPERATION

CATEGORY A - TANDEM THRUST BEARINGS, CONSTANT SPEED - MOTOR DRIVEN TESTER (FIGURES 7, 8 AND 9)

BUILDUP NO.	NO. OF TESTS	PART NO.	SHAFT SPEED RPM	THRUST LOAD LBS	TOTAL DURATION SEC	COOLANT FLUID	COOLANT FLOW RATE GPM/BRG	COOLANT PRESS PSIG	CONFIGURATION DESCRIPTION	RESULTS
1	2	281642	4000	5,000	493	LO_2	7.5	350	New Bearings	
1	2	281642	4000	20,000	85	LO_2	7.5	350		
1	6	281642	4000	35,000	1,392	LO_2	7.6	350		Bearing Reuseable - One Bearing Discolored
2	4	281642	4000	0	541	LO_2	7.7	300	One Set New Bearings. One Set Used in Buildup #1	Bearings Reuseable
3	2	281642	4000	33,000	317	LO_2	7.5	320	Bearings Used in Buildup #2	
3	4	281642	4000	43,000	248	LO_2	7.5	320		
3	4	281642	4000	65,000	67	LO_2	7.5	320		
3	2	281642	4000	33,000	242	LO_2	7.5	320		
3	2	281642	4000	50,000	293	LO_2	7.5	320		
3	2	281642	4000	43,500	248	LO_2	7.5	320		
3	6	281642	4000	45,000	299	LO_2	7.5	315		
3	4	281642	4000	34,000	397	LO_2	7.5	315		
3	2	281642	4000	33,000	552	LO_2	9.0	480		
3	2	281642	4000	33,000	145	LO_2	7.5	315		
3	2	281642	4000	23,000	341	LO_2	7.5	315		Bearing Reuseable with Surface Distress On Races and Signs of Heating on Balls and Races

NOTE: 2 TANDEM BEARING SETS PER BUILDUP.

BEARING TEST RESULTS SUMMARY

PHASE II - QUALIFICATION OF PREFERRED CONFIGURATION FOR TURBOPUMP OPERATION

CATEGORY B - RADIAL BEARING, CONSTANT SPEED - MOTOR DRIVEN TESTER (FIGURES 8 AND 10)

BUILDUP NO.	NO. OF TESTS	PART NO.	SHAFT SPEED RPM	RADIAL LOAD LBS	TOTAL DURATION SEC	FLUID	FLOW RATE GPM/BRG	PRESS PSIG	CONFIGURATION DESCRIPTION	RESULTS
1	10	281644	4000	1000	1970	LO_2	1.4	350	One Brg. Previously Tested in LN_2 One Brg. Previously Tested in LH_2	520 Sec. 10 Sec. Bearings Reuseable.
2	8	281644	4000	1000	541	LO_2	1.4	300	One Brg. Previously Tested In LO_2 One Brg. Previously Tested in LO_2	1576 Sec. 1801 Sec. Bearings Reuseable.
3	16	281644	4000	1000	1415	LO_2	1.4	320	Bearings Used in Buildup #1.	
3	10	281644	4000	1000	696	LO_2	1.4	315		
3	2	281644	4000	1000	552	LO_2	1.7	480		
3	4	281644	4000	1000	486	LO_2	1.4	315		Bearings Reuseable.

NOTE: 2 BEARINGS IN EACH BUILDUP USED AS SLAVE BEARINGS IN TANDEM THRUST BEARING TESTS

BEARING TEST RESULTS SUMMARY

PHASE II - QUALIFICATION OF PREFERRED CONFIGURATION FOR TURBOPUMP OPERATION

CATEGORY C - TANDEM THRUST BEARING, CONSTANT SPEED - PTA TESTER (FIGURES 11 AND 12)

BUILDUP NO.	NO. OF TESTS	PART NO.	SHAFT SPEED RPM	THRUST LOAD LBS	TOTAL DURATION SEC	COOLANT FLUID	COOLANT FLOW RATE GPM/BRG	COOLANT PRESS PSIG	CONFIGURATION DESCRIPTION	RESULTS
1	2	281642	1000	11,000	68	LO_2	8.5	410	New Bearings	
1	2	281642	2000	17,000	553	LO_2	8.5	410		
1	2	281642	3000	25,000	152	LO_2	8.5	410		
1	-	281642	4000	39,000	138	LO_2	8.5	410		
1	8	281642	4000	34,000	2,035	LO_2	8.5	410		
1	2	281642	4000	34,000	297	LO_2	8.5	540		
1	2	281642	4000	28,000	34	LO_2	8.5	450		Bearings Reuseable.

NOTE: TWO TANDEM BEARING SETS PER PTA BUILDUP

BEARING TEST RESULTS SUMMARY

PHASE IV - TURBOPUMP EVALUATION

CATEGORY B - TANDEM THRUST & RADIAL BEARINGS - HIGH LOAD, LIQUID NITROGEN COOLANT, HIGH ACCELERATION RATE - TURBOPUMP (FIGURES 1 AND 2)

BUILDUP NO.	NO. OF TESTS	PART NO.	SHAFT SPEED RPM	THRUST LOAD LBS	TOTAL DURATION SEC	COOLANT FLUID	COOLANT FLOW RATE GPM	COOLANT PRESS PSIG	CONFIGURATION DESCRIPTION	RESULTS
2	1.2 - 08 - EHP - 001	700797 281643 281644	2098	1,230	16	LN_2	25.93	197	New Bearing	
2	1.2 - 08 - EHP - 002	700797 281643 281644	2085	- 1,300	13	LN_2	25.02	192	New Bearing	
2	1.2 - 08 - EHP - 003	700797 281643 281644	2061	- 2,820	9	LN_2	25.60	165	New Bearing	
2	1.2 - 08 - EHP - 004	700797 281643 281644	2098	- 6,830	13	LN2	25.32	166	New Bearing	
2	1-2 - 08 - EHP - 005	700797 281643 281644	2384	+ 4,446	3	LN_2	27.75	220	New Bearing	
2	1.2 - 08 - EHP - 006	700797 281643 281644	2838	+40,500	11	LN_2	32.37	285	New Bearing	
2	1.2 - 08 - EHP - 007	700797 281643 281644	3174	+37,453	6	LN_2	36.6	160	New Bearing	
2	1.2 - 08 - EHP - 008	700797 281643 281644	2918	+25,300	6	LN_2		120	New Bearing	
2	1.2 - 08 - EHP - 009	700797 281643 281644	3258	+49,600	11	LN_2	38.38	280	New Bearing	
2	1.2 - 08 - EHP - 010	700797 281643 281644	3652	+67,000	11	LN_2	42.65	360	New Bearing	
2	1.2 - 08 - EHP - 011	700797 281643 281644	2110	+ 7,150	9	LN_2	24.76	200	New Bearing	

BEARING TEST RESULTS SUMMARY

PHASE IV - TURBOPUMP EVALUATION

CATEGORY A - TANDEM THRUST & RADIAL BEARINGS - REVERSED LOAD,
LIQUID NITROGEN COOLANT - TURBOPUMP (FIGURES 1 AND 2)

BUILDUP NO.	NO. OF TESTS	PART NO.	SHAFT SPEED RPM	THRUST LOAD LBS	TOTAL DURATION SEC	COOLANT FLUID	COOLANT FLOW RATE GPM	COOLANT PRESS PSIG	CONFIGURATION DESCRIPTION	RESULTS
1	6.0 - 04 - EHP - 001	700797 281643 281644	2303	18,760	18	LN_2	30.8	198	New Bearings	
1	6.0 - 04 - EHP - 002	700797 281643 281644	2086	11,000	22	LN_2	29.6	202	New Bearings	
1	6.0 - 04 - EHP - 003	700797 281643 281644	2066	14,850	19	LN_2	29.8	174	New Bearings	
1	6.0 - 04 - EHP - 004	700797 281643 281644	2105	15,100	20	LN_2	24.4	172	New Bearings	
1	6.0 - 04 EHP - 005	700797 281643 281644	2100	7,250	16	LN_2	26.3	119	New Bearings	
1	6.0 - 04 - EHP - 006	700797 281643 281644	2110	2,550	19	LN_2	29.9	161	New Bearings	
1	6.0 - 04 - EHP - 007	700797 281643 281644	1510	4,200	33	LN_2	22.5	176	New Bearings	
1	6.0 - 04 - EHP - 008	700797 281643 281644	2096	9,000	17	LN_2	23	142	New Bearings	
1	6.0 - 04 - EHP - 009	700797 281643 281644	2440	38,100	15	LN_2	30	181	New Bearings	
1	6.0 - 04 - EHP - 010	700797 281643 281644	2431	39,277	17	LN_2	30.6	196	New Bearings	Bearings Reuseable With Discolored Balls and Races Due to Heating

NOTE: TYPICAL COOLANT FLOW SPLIT - 700797 - 21 GPM, 281643 - 3.5 GPM, 281644 - 3.5 GPM

BEARING TEST RESULTS SUMMARY

PHASE II - QUALIFICATION OF PREFERRED CONFIGURATION FOR TURBOPUMP OPERATION

CATEGORY D - RADIAL BEARING -CONSTANT SPEED - PTA TESTER (FIGURES 11 AND 12)

BUILDUP NO.	NO. OF TESTS	PART NO.	SHAFT SPEED RPM	RADIAL LOAD LBS	TOTAL DURATION SEC	COOLANT			CONFIGURATION DESCRIPTION	RESULTS
						FLUID	FLOW RATE GPM/BRG	PRESS PSIG		
1	2	281643	1000	500	68	LO_2	2	410	New Bearings	
1	2	281644	1000	1,000	68	LO_2	2	410	New Bearings	
1	2	281643	2000	4,700	553	LO_2	2	410		
1	2	281644	2000	12,000	553	LO_2	2	410		
1	2	281643	3000	4,900	152	LO_2	2	410		
1	2	281644	3000	13,000	152	LO_2	2	410		
1	-	281643	4000	5,200	138	LO_2	2	410		
1	-	281644	4000	15,000	138	LO_2	2	410		
1	8	281643	4000	5,500	2,035	LO_2	2	410		
1	8	281644	4000	15,500	2,035	LO_2	2	410		
1	2	281643	4000	5,300	297	LO_2	2	540		
1	2	281644	4000	15,000	297	LO_2	2	540		
1	2	281643	4000	4,000	39	LO_2	2	450		Bearings Reuseable.
1	2	281644	4000	12,000	39	LO_2	2	450		Bearings Reuseable.
NOTE:	FOUR BEARINGS	PER BUILDUP.								

BEARING TEST RESULTS SUMMARY

PHASE III - PERIPHERAL EVALUATION OF PROTOTYPE CONFIGURATION

CATEGORY A - TANDEM THRUST BEARINGS, CONSTANT SPEED - REVERSED LOAD, LIQUID NITROGEN COOLED, LOW VAPOR PRESSURE - MOTOR DRIVEN TESTER (FIGURES 7, 8 AND 9)

BUILDUP NO.	NO. OF TESTS	PART NO.	SHAFT SPEED RPM	THRUST RADIAL LOAD LBS	TOTAL DURATION SEC	COOLANT			CONFIGURATION DESCRIPTION	RESULTS
						FLUID	FLOW RATE GPM/BRG	PRESS PSIG		
1	2	281642 700797 281644	2500	23,000 1,000	30	LN_2	6.75 6.75 2.5	150	New Bearing	
1	1	281642 700797 281644	2500	24,000 1,000	21	LN_2	6.75 6.75 2.5	150		
1	2	281642 700797 281644	2500	33,000 1,000	61	LN_2	10.75 10.75 4.5	150		Bearings Reuseable With One Bearing (P/N 281642) Showing Signs of Heating on the Balls and Races
2*	2	700797 281644	2500	22,000 1,000	50	LN_2	10.75 4.5	450	One New Bearing (P/N 700797) One Bearing From Buildup #1	
2*	2	700797 281644	2500	22,000 1,000	194	LN_2	10.75 4.5	260		
2*	2	700797 281644	2500	24,000 1,000	41	LN_2	10.75 4.5	253		
2*	2	700797 281644	2500	27,000 1,000	41	LN_2	10.75 4.5	254		
2*	2	700797 281644	2500	29,000 1,000	47	LN_2	10.75 4.5	254		
2*	2	700797 281644	2500	32,000 1,000	14	LN_2	10.75 4.5	254		Temperature Rose 41° in the Last 20 Seconds* of Test.
3	1	700797 281644	2500	30,000 1,000	334	LN_2	10.75 4.5	214		Bearings Reuseable With Signs of Heating of Balls and Races All Bearings.

NOTE: P/N 700797 IS BEARING EVALUATED UNDER REVERSED LOAD.

* BUILD-UP 2 WAS ONE CONTINUOUS TEST RUN OF 387 SEC DURATION AT VARYING THRUST LOADS, BEARING FLOW RATES, AND PRESSURES.

BEARING TEST RESULTS SUMMARY

PHASE IV - TURBOPUMP EVALUATION

CATEGORY B - TANDEM THRUST & RADIAL BEARINGS - HIGH LOAD, LIQUID NITROGEN COOLANT, HIGH ACCELERATION RATE - TURBOPUMP (FIGURES 1 AND 2)

BUILDUP NO.	NO. OF TESTS	PART NO.	SHAFT SPEED RPM	THRUST LOAD LBS	TOTAL DURATION SEC	COOLANT			CONFIGURATION DESCRIPTION	RESULTS
						FLUID	FLOW RATE GPM	PRESS PSIG		
2	1.2 - 08 - EHP - 012	700797 281643 281644	2101	+13,320	20	LN_2	24.73	220	New Bearing	
2	1.2 - 08 - EHP - 013	700797 281643 281644	3577	+41,500	11	LN_2	24.9	360	New Bearing	
2	1.2 - 08 - EHP - 014	700797 281643 281644	3697	+60,400	9	LN_2	25.2	440	New Bearing	

NOTE: + THRUST IS TOWARD PUMP, - THRUST IS TOWARD TURBINE.

REPORT NASA CR 54816 DISTRIBUTION LIST

W. F. Dankhoff (5 copies)
NASA
Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135
Mail Stop 500-305

J. A. Durica (1 copy)
Mail Stop 500-210

Patent Counsel (1 copy)
Mail Stop 77-1

Lewis Library (2 copies)
Mail Stop 3-7

Lewis Technical Information
Division (1 copy)
Mail Stop 5-5

W. W. Wilcox (1 copy)
Mail Stop 500-305

M. J. Hartmann (1 copy)
Mail Stop 5-9

J. C. Montgomery (1 copy)
Mail Stop 501-1

Major E. H. Karelis (1 copy)
AFSC Liaison Office
Mail Stop 4-1

Lewis Office of Reliability
and Quality Assurance (1 copy)
Mail Stop 500-203

F. J. Dutee (1 copy)
Mail Stop 23-1

D. F. Lange (1 copy)
Mail Stop 501-1

W. J. Anderson (1 copy)
Mail Stop 6-1

NASA Headquarters (6 copies)
Technical Information Abstracting
and Dissemination Facility
NASA Scientific and Technical
Information Facility
Box 5700
Bethesda, Maryland

Library (1 copy)
NASA
Ames Research Center
Moffett Field, California 94035

Library (1 copy)
NASA
Flight Research Center
P. O. Box 273
Edwards AFB, California 93523

Library (1 copy)
NASA
Goddard Space Flight Center
Greenbelt, Maryland 20771

Library (1 copy)
NASA
Langley Research Center
Langley Station
Hampton, Virginia 23365

Library (1 copy)
NASA
Manned Spacecraft Center
Houston, Texas 77058

Library (1 copy)
NASA
George C. Marshall Space Flight Center
Huntsville, Alabama 35812

Library (1 copy)
NASA
Western Operations Office
150 Pico Boulevard
Santa Monica, California 90406

Library (1 copy)
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91103

A. O. Tischler (2 copies)
NASA Headquarters
Code RP
Washington, D. C. 20546

J. W. Thomas, Jr. (5 copies)
NASA
George C. Marshall Space Flight Center
I-E-E
Huntsville, Alabama 35812

Dr. E. B. Konecci (1 copy)
National Aeronautics and Space
Council
Executive Office of the President
Executive Office Building
Washington, D.C.

H. V. Main (1 copy)
Air Force Rocket Propulsion
Laboratory
Edwards Air Force Base
Edwards, California

T. Iura (1 copy)
Aerospace Corporation
2400 East El Segundo Blvd.
P. O. Box 95085
Los Angeles, California 90045

Pratt and Whitney Aircraft
Corporation (1 copy)
Florida Research and Development
Center
P. O. Box 2691
West Palm Beach, Florida 33402

Rocketdyne (Library Department 586-306)
(1 copy)
Division of North American Aviation
6633 Canoga Avenue
Canoga Park, California 91304
Attention: Dr. Kurt Rothe

Hudson Scheifle (1 copy)
Bower Roller Bearing Division
3040 Hart Avenue
Detroit, Michigan

R. P. Remorenko (1 copy)
The Fafnir Bearing Company
37 Booth Street
New Britain, Connecticut

H. Hanay (1 copy)
Industrial Tectronics, Inc.
18301 Santa Fe Avenue
Compton, California

John H. Johnson (1 copy)
Marlin-Rockwell Corporation
402 Chandler Street
Jamestown, New York

Richard Matt (1 copy)
New Departure Division of
General Motors Corporation
269 N. Mail Street
Bristol Connecticut

Tibor Tallian (1 copy)
SKF Industries, Inc.
1100 First Avenue
King of Prussia, Pennsylvania

Richard Shevchenko (1 copy)
Pratt & Whitney Aircraft
Division of United Aircraft Corp.
400 Main Street
E. Hartford 8, Connecticut

Myles Butner (1 copy)
Rocketdyne
Division of North American Aviation
6633 Canoga Avenue
Canoga Park, California 91304

Frank Schweiger (1 copy)
Flight Propulsion Division
Large Jet Engine Department
Cincinnati 15, Ohio
Mail Stop K-49

J. M. Ross (1 copy)
Cleveland Graphite Bronze
Division of Clevite Corp.
17000 St. Clair
Cleveland, Ohio 44110