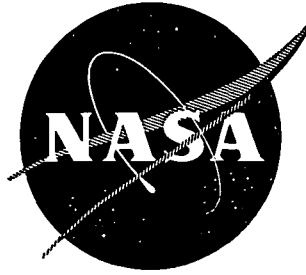


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NASA CR-120820



## FLUORINE LUBRICATED BEARING TECHNOLOGY

# CASE FILE COPY

by

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prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center

Contract NAS 3-11201

W. Britsch, Project Manager

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| 16. Abstract<br><br>An experimental program was conducted to evaluate and select materials for ball bearings intended for use in liquid fluorine and/or FLOX. The ability of three different ball-separator materials, each containing nickel, to form and transfer a nickel fluoride film to provide effective lubrication at the required areas of a ball bearing operating in liquid fluorine was evaluated. In addition, solid lubrication of a ball bearing operating in liquid fluorine by either a fused fluoride coating applied to all surfaces of the ball separator or by a fluoride impregnation of porous sintered material ball separators was evaluated. Less bearing wear occurred when tests were conducted in the less reactive FLOX. Bearings fabricated from any of the materials tested would have relatively short wear lives and would require frequent replacement in a reusable engine. |  |                                                      |  |                                                            |  |
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## FOREWORD

This final report is a summary of the work performed by the Aerojet Liquid Rocket Company, Sacramento, California, under Contract NAS 3-11201 (Fluoride Lubricated Bearing Technology). The contract was sponsored by the Lewis Research Center of the National Aeronautics and Space Administration and was administered under the technical direction of the Chemical Rocket Division with Mr. W. Britsch as Project Engineer. Mr. Herbert Scibbe of the Fluid System Components Division was Technical Adviser.



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# ABSTRACT

An experimental program was conducted to evaluate and select materials for ball bearings intended for use in liquid fluorine and/or FLOX. The ability of three different ball-separator materials, each containing nickel, to form and transfer a nickel fluoride film to provide effective lubrication at the required areas of a ball bearing operating in liquid fluorine was evaluated. In addition, solid lubrication of a ball bearing operating in liquid fluorine by either a fused fluoride coating applied to all surfaces of the ball separator or by a fluoride impregnation of porous sintered material ball separators was evaluated. Less bearing wear occurred when tests were conducted in the less reactive FLOX. Bearings fabricated from any of the materials tested would have relatively short wear lives and would require frequent replacement in a reusable engine.

## I. SUMMARY

The primary objective of the "Fluorine Lubricated Bearing Technology" program was to evaluate materials for FLOX and fluorine-cooled bearings. Of particular interest were the capability of transferring metallic fluoride films from the cage to the ball/race contact zone, and the lubricating qualities and load sustaining capacity of the transferred films. Tests of 15 minutes duration were conducted first in liquid fluorine using cages of HyMu 80, Rene' 41, Berylco nickel 440, and air melt 440C bearing element surplus from another program. Speed and axial load were varied in discrete combinations of 7,000, 14,000, 20,000 rpm and 400, 800, 1,200 pounds (1790, 3590, 5380N) for each of the three cage materials, to result in a 27 test matrix. Wear measurements of the cage and bearing elements were made after each test so that wear data could be acquired as functions of speed and load. Test results were inconclusive in that no one cage material appeared to be superior to any other. In general, ball wear appeared to increase linearly with both load and speed up to 14,000 rpm, after which the wear rate increased rapidly.

A new bearing was designed to better optimize internal geometry and new cages and bearings were procured. The same cage materials previously used were included together with a Berylco nickel 440 cage coated with a 76-24 mix of calcium difluoride and lithium fluoride. In addition, two cages of sintered Inconel 600 were impregnated with both lithium fluoride and the calcium difluoride lithium fluoride mix.

All six cage materials were tested in liquid fluorine at 20,000 rpm and 1,000 pounds (4448N) axial load for one hour duration. Excessive ball wear (0.010 in. (0.25 mm)) occurred on all test specimens. To alleviate this condition, thought to result from ball speed variation (BSV), a local relief was incorporated in the inner race to unload each ball approximately once each revolution and thus prevent accumulative effects of BSV. This modification proved to be ineffective and ball wear in liquid fluorine remained high.

Tests in FLOX of identical bearings with Berylco 440 nickel cages indicated that cage wear was comparable to that experienced with liquid fluorine. However, ball wear was only 25%. Because of a reduction in program scope, one hour tests on the remaining 5 cage materials were not performed so that the number of FLOX tested specimens was small compared to the number tested in liquid fluorine. However, analysis of wear data variation leads to the conclusion that the results are real and not caused by sample size. Since the mechanical aspects of the tests were maintained (i.e., load speed materials, etc.), a real difference in "bearing lubrication" between liquid fluorine and FLOX is presumed to exist. The exact mechanism is unknown but is believed to be a function of chemical reactivity between the test fluid and the bearing/cage materials; specifically, the rate of formation of iron difluoride ( $\text{FeF}_2$ ). The combination of inner race ball spin and surface compressive stress (SV)<sup>2</sup> may remove the fluoride film as fast as it is formed so that the ball race wear rate is smaller in the less reactive FLOX. The wear rate in either fluid is considered to be larger than could be tolerated for bearings used in a liquid fluorine engine turbopump.

## II. INTRODUCTION

The purpose of this program was to conduct an experimental evaluation of several candidate cage materials operating with 50 mm (210) ball bearings in both liquid fluorine and 82.6% FLOX. The lubricating characteristics of the fluoride films formed by the reaction of the cage materials with fluorine and FLOX was assessed. The transfer of these films from the cage to the ball-race contact zone and their effect on bearing load capacity and wear also was evaluated. The program established design criteria and material data required for future space storable engines utilizing liquid fluorine or FLOX as oxidizer. The program comprised a five-task effort, as follows:

- . Task I - Material Evaluation

Design, fabrication, and evaluation of ball separators of three high nickel content materials: Berylco Nickel 440, HyMu 80, and Rene' 41. Existing 440c ball bearing rings and balls were used in these evaluation tests.

- . Task II - Bearing Design

Design of a ball bearing with internal geometry optimized for a sustained mean Hertz stress of 250,000 psi ( $1.724 \times 10^9$  N/m<sup>2</sup>) and a DN value of  $1.0 \times 10^6$ . Design of ball separators for this bearing.

- . Task III - Bearing Fabrication

Fabrication of the Task II ball bearing and ball separator designs. The balls and races were fabricated from CEVM 440c. The ball separators were fabricated from the following six materials:

HyMu 80 (annealed)

Rene' 41 (annealed)

Berylco Nickel 440 (annealed)

Berylco Nickel 440 with a fused coating of a mixture of 76% calcium fluoride and 24% lithium fluoride

Sintered Inco 600; 40% porosity, and impregnated with lithium fluoride

Sintered Inco 600, 40% porosity and impregnated with a mixture of 76% calcium fluoride and 24% lithium fluoride.



## II, Introduction (cont.)

### Task IV - One-Hour Bearing Evaluation Tests in Liquid Fluorine

Ball bearings fabricated under Task III were subjected to tests of one-hour duration in fluorine at 20,000 rpm and an axial load of 1000 lb (4448N). Comparative tests were conducted on each of the six ball separator materials.

### Task V - One-Hour Bearing Evaluation Tests in Flox

Ball bearings fabricated under Task III with selected ball separator materials were subjected to the Task IV test conditions, except the test fluid was 83.6% FLOX.

At the onset of this program there was little specific information that could be used in establishing criteria for materials for high-speed, high-load, fluorine-lubricated bearings. However, such useful information as could be found was applied in selecting the candidate bearing materials. Some of the previously completed investigations considered pertinent to this program are briefly summarized below:

The fluorine-lubricated bearing tests by Bell Aerosystems in the "Chariot" Program (Ref 1) were conducted at DN values and loads considerably lower than those on this program. The DN values were  $0.25 \times 10^6$ , axial loads were 60 lb (222N), and radial loads were 136 lb (605N). However, the tests were conducted for appreciable durations (276 to 2520 sec). In eight successful tests 205 size (25 mm bore) ball bearings were used with AISI 440c races and balls and two-piece riveted S Monel cages. These tests provided baseline bearing data and justified the selection of AISI 440c for races and balls for this program's ball separator material evaluation tests.

Many studies have been performed to determine the compatibility of various metals with fluorine. Most metals show little or no sign of corrosion when they are properly cleaned, passivated, and are not contaminated with moisture prior to their exposure to fluorine. The stainless steels and nickel are considered excellent for fluorine service. A series of tests (Ref 2) conducted by NASA Lewis Research Center showed that no measurable physical erosion, and no chemical attack occurred with nickel, stainless steel, aluminum or grass specimens at flow velocities up to 400 fps (122 m/sec) at 140°R (78°K) and pressures up to 1500 psig ( $1.03 \times 10^7$  N/m<sup>2</sup>).

Compatibility of polymeric materials was also investigated at NASA Lewis Research Center (Ref 3). Both static and dynamic tests were conducted on various polymeric materials, some of which are commonly used for nonmetallic ball or roller separators in propellant service rolling element bearings. While several materials survived the static tests, all either exploded or burned

## II, Introduction (cont.)

slowly during the dynamic flow tests. Pure polytetrafluorethylene (PTFE) was the most compatible non-metallic material tested; no reaction occurred until the fluorine flow velocity was above 220 fps (67 m/sec), then the reaction was slow burning. However, impregnates, such as glass or nickel commonly used with PTFE bearing cages significantly lowered the flow velocity at which ignition occurred. From the results of this investigation it was concluded that the use of non-metallics for fluorine-lubricated bearing separators could not be justified especially since rubbing contact tests had not been conducted.

Another study (Ref 4) by NASA Lewis Research Center was concerned with friction, wear, and dynamic sealing in liquid fluorine. In this study it was revealed that the presence of a fluoride film was effective in reducing both friction and wear of sliding surfaces. The naturally formed film was identified as nickel fluoride when using K-162B (titanium carbide with a nickel binder) and aluminum oxide as the disk and rider. The fact that this film provided effective lubrication was substantiated by comparative tests in liquid oxygen during which the coefficient of friction was approximately 4 times and the wear of the K-162B disk was approximately 10 times that measured in liquid fluorine. This data indicated that a possible method of providing effective lubrication to a ball bearing operating in liquid fluorine would be to utilize ball separators of materials with high nickel content.

### III. MATERIAL EVALUATION (TASK I)

This task was comprised of three subtasks and had for its end purpose, the preliminary evaluation of three bearing separator materials - HyMu 80, Rene' 41, and Berylco Nickel 440. The subtasks included the design of a bearing test head, the design of a bearing separator for use with surplus 210 size bearings, and the testing of these bearings in a liquid fluorine environment. Characteristics of the test bearings and separator (cage) are described in Section IV, Bearing Design and Analysis (Task II), where they can be compared directly to the features of the final bearing design. The tester, test setup, and operating procedures have been described in detail in a separate section (IX), since the essence of this task was to assess the relative merits of the three materials in providing lubricating fluoride films.

A test matrix of 27 tests was conducted. Nine pairs of bearings (18 bearings) were divided into three groups, each group having two ball separators fabricated from the three selected materials: HyMu 80, Rene' 41, and Berylco Nickel 440. The test plan was that each group be tested at the same speeds for the same durations: 15 min at 7000 rpm, 15 min at 14,000 rpm, and 15 min at 20,000 rpm. This, then, would result in total accrued test times of 45 min on all bearing samples. Applied axial load was the only variable. Group 1 bearings were tested at 400 lb (1779N), group 2 bearings at 800 lb (3558N), and group 3 bearings at 1200 lb (5338N). Post test inspections were performed after each 15 min test. This inspection consisted of a microscopic examination and dimensional and weight measurements of the individual bearing components. Care was taken to assure that each ball was placed in the same separator pocket on each reassembly.

Tables I, II, and III are tabulations of steady-state data for these tests which begin with test number 10. The first nine tests (not tabulated) were checkout tests for the tester and test setup. Liquid nitrogen was the test fluid for the checkout tests. Tests 31, 32, and 33 were special unscheduled tests. Since they were conducted with liquid fluorine they have been included in this report. The reasons for conducting these tests is given in the next paragraph. Test 42 was the last of the 27 scheduled material evaluation tests.

Some difficulties were experienced in the operation of the test rig. ~~The first test (10) was terminated prematurely because of (apparent) bearing torque fluctuations although no bearing damage was found after disassembly.~~ Early shutdown also was required on all three of the 800 lb (3558N) 20,000 rpm load tests because of a high level of vibration. Again, no bearing damage was found.

An investigation indicated that the turbine drive assembly was the source of the vibration. The drive was disassembled and it was found that the hydrostatic thrust bearing had rubbed and that wear debris was trapped between the rotating and stationary surfaces. The turbine drive was replaced with a spare assembly and test 31, 32, and 33 were conducted. The purpose of these tests was to determine if replacement of the drive had eliminated the vibration problem. If the problem still existed these tests were planned to yield data

TABLE I

## TASK I 400-LB LOAD TEST SERIES STEADY-STATE DATA

| Test No. | Separator Material  | Date     | Duration, min | Speed, RPM | LP <sub>2</sub> Flow, gpm<br>(m <sup>3</sup> /min) | Axial Load                    |                                 | Temperature                               |                             |                               |                                          | Remarks                                                                                                                                                               |
|----------|---------------------|----------|---------------|------------|----------------------------------------------------|-------------------------------|---------------------------------|-------------------------------------------|-----------------------------|-------------------------------|------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|          |                     |          |               |            |                                                    | Upstream Bearing, lb f<br>(N) | Downstream Bearing, lb f<br>(N) | LP <sub>2</sub> Inlet, Bearing, °R<br>(K) | Upstream Bearing, °R<br>(K) | Downstream Bearing, °R<br>(K) | LP <sub>2</sub> Exit, Bearing, °R<br>(K) |                                                                                                                                                                       |
| 10       | Berylico Nickel 440 | 7/15/68  | 11.5          | 7000       | 7.5<br>(.0284)                                     | 331<br>(1472)                 | 422<br>(1877)                   | 167<br>(93)                               | 163<br>(91)                 | 166<br>(92)                   | 168<br>(93)                              | Premature shutdown due to erratic torque readings. No problem noted on posttest inspection. Bearings scheduled for test 013.                                          |
| 11       | HyMu 80             | 7/16/68  | 15            | 7000       | 7.5<br>(.0284)                                     | 331<br>(1472)                 | 429<br>(1908)                   | 167<br>(93)                               | 168<br>(93)                 | 165<br>(92)                   | 167<br>(93)                              | Bearings scheduled for test 014.                                                                                                                                      |
| 12       | Rene' 41            | 7/17/68  | 15            | 6800       | 7.4<br>(.0280)                                     | 320<br>(1423)                 | 425<br>(1890)                   | 168<br>(93)                               | 165<br>(92)                 | 167<br>(93)                   | 169<br>(94)                              | Bearings scheduled for test 015.                                                                                                                                      |
| 13a      | Berylico Nickel 440 | 7/18/68  | 3.5           | 7050       | 7.5<br>(.0284)                                     | 331<br>(1472)                 | 421<br>(1873)                   | 164<br>(91)                               | 161<br>(89)                 | 164<br>(91)                   | 167<br>(93)                              | Bearings from test 010 made up time required for 15 min. at 7000 RPM. No inspection performed. Conducted 15 min. test at 14,000 RPM. Bearings scheduled for test 016. |
| 13b      | Berylico Nickel 440 | 7/18/68  | 15            | 13,900     | 7.6<br>(.0288)                                     | 336<br>(1495)                 | 427<br>(1800)                   | 170<br>(94)                               | 168<br>(93)                 | 174<br>(97)                   | 175<br>(97)                              | Bearings scheduled for test 017.                                                                                                                                      |
| 14       | HyMu 80             | 7/19/68  | 15            | 14,000     | 7.6<br>(.0288)                                     | 432<br>(1521)                 | 433<br>(1926)                   | 164<br>(91)                               | 166<br>(92)                 | 168<br>(93)                   | 168<br>(93)                              | Bearings scheduled for test 018.                                                                                                                                      |
| 15       | Rene' 41            | 10/8/68  | 15            | 13,900     | 7.9<br>(.0299)                                     | 358<br>(1592)                 | 449<br>(1977)                   | 174<br>(97)                               | 160<br>(89)                 | 172<br>(96)                   | 174<br>(97)                              | Total of 45 minutes accrued on bearings.                                                                                                                              |
| 16       | Berylico Nickel 440 | 10/9/68  | 15            | 20,000     | 8.1<br>(.0307)                                     | 392<br>(1743)                 | 474<br>(2108)                   | 165<br>(92)                               | 183<br>(102)                | 195<br>(108)                  | 179<br>(99)                              | Total of 45 minutes accrued on bearings.                                                                                                                              |
| 17       | HyMu 80             | 10/10/68 | 15            | 20,000     | 8.7<br>(.0329)                                     | 442<br>(1966)                 | 503<br>(2237)                   | 168<br>(93)                               | 165<br>(97)                 | 175<br>(98)                   | 176<br>(98)                              | Total of 45 minutes accrued on bearings.                                                                                                                              |
| 18       | Rene' 41            | 10/11/68 | 15            | 20,000     | 8.6<br>(.0326)                                     | 408<br>(1814)                 | 493<br>(2193)                   | 178<br>(99)                               | 183<br>(102)                | 191<br>(106)                  | 193<br>(107)                             | Total of 45 minutes accrued on bearings.                                                                                                                              |

TABLE II

## TASK I 800-LB LOAD TEST SERIES STEADY-STATE DATA

| Test No. | Separator Material | Date     | Duration, min | Speed, RPM | LP Flow, gpm                         |                                     | Axial Load                           |                                     | Temperatures                       |                                   | Remarks                                                                                                                                                                                                                                  |
|----------|--------------------|----------|---------------|------------|--------------------------------------|-------------------------------------|--------------------------------------|-------------------------------------|------------------------------------|-----------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|          |                    |          |               |            | LP <sub>2</sub> Inlet, Bearing, lb f | LP <sub>2</sub> Exit, Bearing, lb f | LP <sub>2</sub> Inlet, Bearing, lb f | LP <sub>2</sub> Exit, Bearing, lb f | LP <sub>2</sub> Inlet, Bearing, °R | LP <sub>2</sub> Exit, Bearing, °R |                                                                                                                                                                                                                                          |
| 19       | HyMu 80            | 10/21/68 | 15            | 7250       | 14.3<br>(.0541)                      | 813<br>(3616)                       | 168<br>(93)                          | 174<br>(97)                         | 164<br>(91)                        | 170<br>(94)                       | Bearings scheduled for test 022.                                                                                                                                                                                                         |
| 20       | Berylco Nickel 440 | 10/22/68 | 15            | 7250       | 15.0<br>(.0568)                      | 884<br>(3932)                       | 163<br>(91)                          | 174<br>(97)                         | 160<br>(89)                        | 163<br>(91)                       | Bearings scheduled for test 023.                                                                                                                                                                                                         |
| 21       | Rene' 41           | 10/23/68 | 15            | 7375       | 15.3<br>(.0579)                      | 895<br>(3981)                       | 170<br>(94)                          | 164<br>(91)                         | 160<br>(89)                        | 165<br>(92)                       | Bearings scheduled for test 024.                                                                                                                                                                                                         |
| 22       | HyMu 80            | 10/24/68 | 15            | 14,000     | 14.8<br>(.0560)                      | 895<br>(3981)                       | 163<br>(91)                          | 164<br>(91)                         | 160<br>(89)                        | 163<br>(91)                       | Bearings scheduled for test 025.                                                                                                                                                                                                         |
| 23       | Berylco Nickel 440 | 10/25/68 | 15            | 14,000     | 14.6<br>(.0553)                      | 836<br>(3719)                       | 173<br>(96)                          | 183<br>(102)                        | 163<br>(91)                        | 172<br>(96)                       | Bearings scheduled for test 026.                                                                                                                                                                                                         |
| 24       | Rene' 41           | 11/5/68  | 15            | 14,000     | 14.7<br>(.0556)                      | 857<br>(3812)                       | 163<br>(91)                          | 164<br>(91)                         | 160<br>(89)                        | 163<br>(91)                       | Bearings scheduled for test 027.                                                                                                                                                                                                         |
| 25       | HyMu 80            | 11/6/68  | 4.2           | 19,800     | 14.5<br>(.0549)                      | 829<br>(3687)                       | 165<br>(92)                          | 180<br>(100)                        | 164<br>(91)                        | 174<br>(97)                       | Premature shutdown due to high vibration. Total accrued time of 34.2 min on bearings.                                                                                                                                                    |
| 26       | Berylco Nickel 440 | 11/7/68  | 3.4           | 20,000     | 15.0<br>(.0568)                      | 833<br>(3705)                       | 174<br>(97)                          | 183<br>(102)                        | 160<br>(89)                        | 178<br>(99)                       | Premature shutdown due to high vibration. Total accrued time of 33.4 min on bearings.                                                                                                                                                    |
| 27       | Rene' 41           | 11/8/68  | 5.2           | 19,900     | 14.7<br>(.0556)                      | 814<br>(3621)                       | 174<br>(97)                          | 191<br>(106)                        | 164<br>(91)                        | 177<br>(98)                       | Premature shutdown due to high vibration. Total accrued time of 33.2 min on bearings. Disassembled drive unit and found hydrostatic thrust bearing faces scored and metal chips between faces. Replaced drive unit for next test series. |

TABLE III

## TASK I 1200-LB LOAD TEST SERIES STEADY-STATE DATA

| Test No. | Separator Material | Date    | Duration, min | Speed, RPM | LF <sub>2</sub> Flow, gpm (m <sup>3</sup> /min) | Axial Load                            |                                         | Temperatures                   |                           |                             |                               | Remarks                                                                                                                        |
|----------|--------------------|---------|---------------|------------|-------------------------------------------------|---------------------------------------|-----------------------------------------|--------------------------------|---------------------------|-----------------------------|-------------------------------|--------------------------------------------------------------------------------------------------------------------------------|
|          |                    |         |               |            |                                                 | Upstream Bearing, lb <sub>f</sub> (N) | Downstream Bearing, lb <sub>f</sub> (N) | LF <sub>2</sub> Inlet, o R (K) | Upstream Bearing, o R (K) | Downstream Bearing, o R (K) | LF <sub>2</sub> Exit, o R (K) |                                                                                                                                |
| 34       | HyMu 80            | 8/4/69  | 15            | 7000       | 14.2<br>(.0538)                                 | 1170<br>(5204)                        | 1352<br>(6014)                          | 167<br>(93)                    | 155<br>(86)               | 165<br>(92)                 | 168<br>(93)                   | Bearings scheduled for test 037                                                                                                |
| 35       | Berylco Nickel 440 | 8/5/69  | 15            | 7250       | 13.8<br>(.0522)                                 | 1103<br>(4906)                        | 1285<br>(5716)                          | 168<br>(93)                    | 163<br>(91)               | 157<br>(87)                 | 173<br>(96)                   | Bearings scheduled for test 038                                                                                                |
| 36       | Rene' 41           | 8/6/69  | 15            | 7000       | 13.7<br>(.0519)                                 | 1100<br>(4893)                        | 1277<br>(5680)                          | 160<br>(89)                    | 169<br>(94)               | 167<br>(93)                 | 165<br>(92)                   | Bearings scheduled for test 039                                                                                                |
| 37       | HyMu 80            | 8/7/69  | 15            | 14,000     | 13.6<br>(.0515)                                 | 1083<br>(4817)                        | 1257<br>(5591)                          | 167<br>(93)                    | 169<br>(94)               | 171<br>(95)                 | 168<br>(93)                   | Bearings scheduled for test 040                                                                                                |
| 38       | Berylco Nickel 440 | 8/11/69 | 15            | 14,000     | 14.0<br>(.0530)                                 | 1150<br>(5115)                        | 1339<br>(5956)                          | 166<br>(92)                    | 168<br>(93)               | 170<br>(94)                 | 173<br>(96)                   | Bearings scheduled for test 041                                                                                                |
| 39       | Rene' 41           | 8/12/69 | 15            | 14,000     | 13.5<br>(.0511)                                 | 1060<br>(4715)                        | 1255<br>(5582)                          | 167<br>(93)                    | 169<br>(94)               | 171<br>(95)                 | 175<br>(97)                   | Bearings scheduled for test 042                                                                                                |
| 40       | HyMu 80            | 8/18/69 | 15            | 19,850     | 13.8<br>(.0522)                                 | 1094<br>(4866)                        | 1283<br>(5707)                          | 170<br>(94)                    | 176<br>(98)               | 185<br>(103)                | 185<br>(103)                  | Total of 45 min. accrued on bearings.                                                                                          |
| 41       | Berylco Nickel 440 | 8/20/69 | 15            | 20,000     | 21.0<br>(.0795)                                 | 995<br>(4426)                         | 1353<br>(6018)                          | 163<br>(91)                    | 164<br>(91)               | 168<br>(93)                 | 168<br>(93)                   | Total of 45 min. accrued on bearings.                                                                                          |
| 42       | Rene' 41           | 8/22/69 | 3.6           | 20,000     | 21.9<br>(.0829)                                 | 1083<br>(4817)                        | 1448<br>(6441)                          | 164<br>(91)                    | 166<br>(92)               | 172<br>(96)                 | 171<br>(95)                   | Kill shutdown because of a sudden increase in torque. Upon disassembly it was discovered that the upstream bearing had failed. |

### III, Material Evaluation (Task I) (cont.)

which would isolate the source so that additional fixes could be made. Two identical tests were planned. These consisted of running at a constant speed, 20,000 rpm. with 5 min of steady-state at each of five load settings (400, 600, 800, 1000, and 1200 lb) (1779, 2670, 3558, 4448, and 5338N). Facility limitations and fluorine loading required that the second of these tests be split into two runs and therefore have a two-test number (32 and 33) identification. Steady-state data is tabulated in Table IV. Operation was smooth during both tests and the Task I testing was resumed.

A bearing failure occurred during the last test (42) of this series. A seizure occurred between the Rene' 41 ball separator and the 440c outer ring guiding land on the downstream side. The bearing was located on the load piston side of the tester, or the upstream position with respect to the fluorine flow. A photograph of the assembled failed bearing is shown in Figure 1. Figure 2 shows Rene' 41 material welded to the outer ring guiding land. It was concluded that a metal chip, probably a separator wear particle from a previous test, became lodged between the separator and land. This chip then caused the seizure which resulted in high torque and early shutdown. Some credence to the chip theory was given when upon the tester overhaul wear particles were indeed found.

The post test measurements of all the bearings from the material evaluation tests are given in Section VIII,A, along with a discussion of the results.

TABLE IV

## TASK I UNSCHEDULED TESTS STEADY-STATE DATA

| Test No. | Separator Material      | Date    | Duration, min | Speed, RPM | LP <sub>2</sub> Flow, gpm<br>(m <sup>3</sup> /min) | Axial Load                               |                                                | Temperatures                     |                             |                               |                                 | Remarks                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |
|----------|-------------------------|---------|---------------|------------|----------------------------------------------------|------------------------------------------|------------------------------------------------|----------------------------------|-----------------------------|-------------------------------|---------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|          |                         |         |               |            |                                                    | Upstream Bearing, lb <sub>f</sub><br>(N) | Downstream Bearing, lb <sub>f</sub><br>(m/min) | LP <sub>2</sub> Inlet, °R<br>(K) | Upstream Bearing, °R<br>(K) | Downstream Bearing, °R<br>(K) | LP <sub>2</sub> Exit, °R<br>(K) |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
| 31       | Berylico Nickel 440     | 6/25/69 | 3             | 20,000     | 7.9<br>(.0299)                                     | 342<br>(1521)                            | 409<br>(1819)                                  | 169<br>(94)                      | 174<br>(97)                 | 183<br>(102)                  | 175<br>(97)                     | High vibration was experienced during all three of the 800-lb 20,000 RPM tests. Turbine drive unit had defective hydrostatic thrust bearing and was replaced by a spare unit. These tests were conducted to determine if vibration was eliminated by the replacement of the drive unit or, if not, how vibration level changed as load was varied at a constant speed of 20,000 RPM. Load was varied each 5 min. from 400 to 1200 lb in 200-lb increments. This was repeated for two fluorine flow rates to see if flow had an effect upon the vibration level. |
|          |                         |         |               |            |                                                    | 519<br>(2309)                            | 607<br>(2700)                                  | 175<br>(97)                      | 179<br>(99)                 | 194<br>(108)                  | 183<br>(102)                    |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
|          |                         |         |               |            |                                                    | 788<br>(3505)                            | 907<br>(4034)                                  | 172<br>(96)                      | 178<br>(99)                 | 194<br>(108)                  | 179<br>(99)                     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
|          |                         |         |               |            |                                                    | 905<br>(4025)                            | 1039<br>(4621)                                 | 179<br>(99)                      | 183<br>(102)                | 194<br>(108)                  | 186<br>(103)                    |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
|          |                         |         |               |            |                                                    | 1092<br>(4857)                           | 1268<br>(5640)                                 | 182<br>(101)                     | 187<br>(104)                | 207<br>(115)                  | 191<br>(106)                    |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
| 32       | Berylico Nickel 440     | 7/28/69 | 5             | 19,750     | 13.4<br>(.0507)                                    | 392<br>(1744)                            | 520<br>(2313)                                  | 174<br>(97)                      | 163<br>(91)                 | 174<br>(97)                   | 181<br>(101)                    |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
|          |                         |         |               |            |                                                    | 486<br>(2162)                            | 656<br>(2918)                                  | 167<br>(93)                      | 155<br>(86)                 | 165<br>(92)                   | 172<br>(96)                     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
|          |                         |         |               |            |                                                    | 696<br>(3096)                            | 915<br>(4070)                                  | 174<br>(97)                      | 163<br>(91)                 | 174<br>(97)                   | 178<br>(99)                     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
|          |                         |         |               |            |                                                    | 867<br>(3856)                            | 1105<br>(4915)                                 | 174<br>(97)                      | 163<br>(91)                 | 174<br>(97)                   | 172<br>(96)                     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
|          |                         |         |               |            |                                                    | 1072<br>(3768)                           | 1370<br>(6094)                                 | 172<br>(96)                      | 155<br>(86)                 | 170<br>(94)                   | 170<br>(94)                     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
| 33       | Same Hardware as in 032 | 8/1/69  | 5             | 20,000     | 20.1<br>(.0761)                                    |                                          |                                                |                                  |                             |                               |                                 |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |





Figure 1. Outer Race, Posttest 1178-D02-OW-042

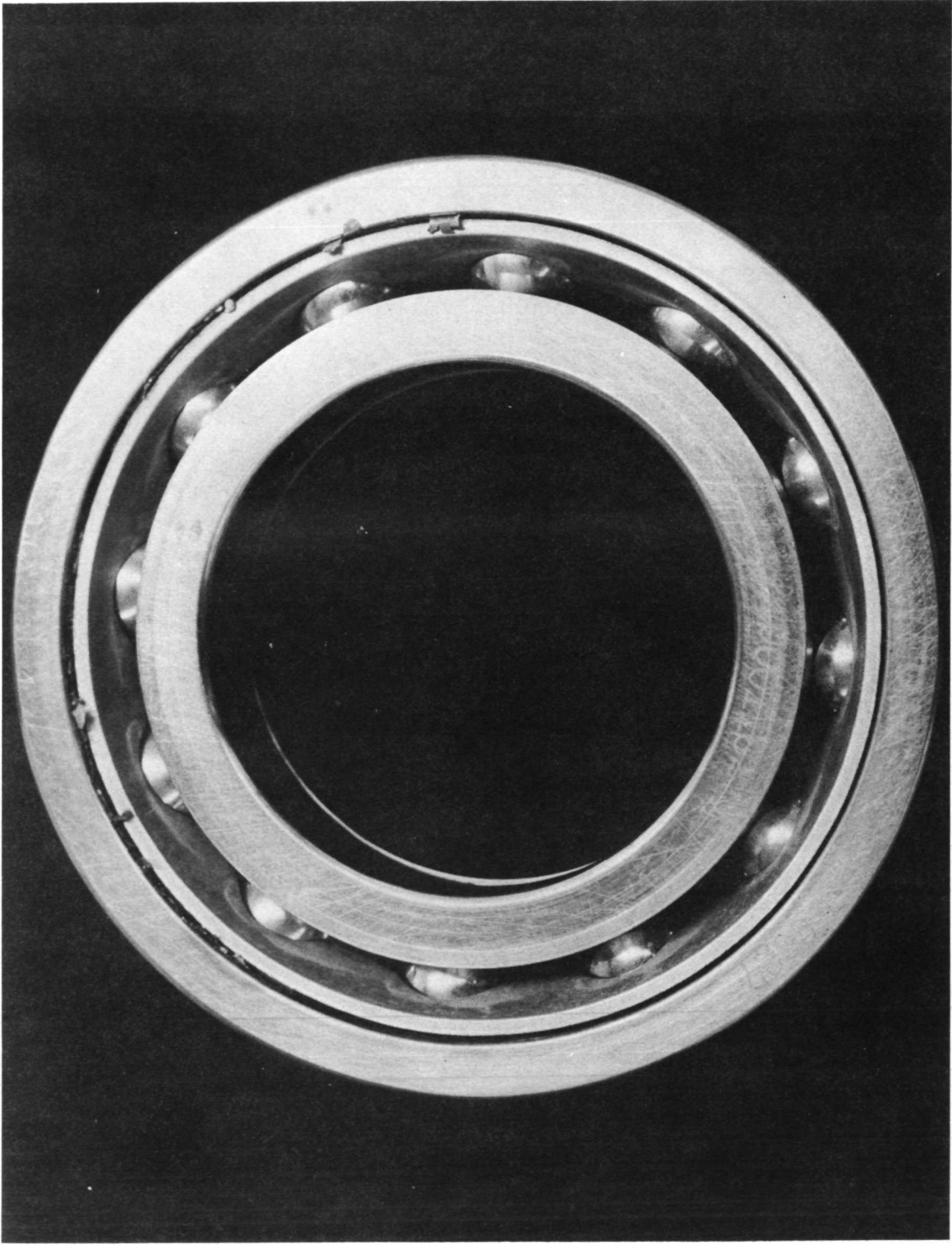


Figure 2. Ball Bearing, Rene' 41 Cage, Posttest 1178-D02-OW-042,  
Downstream

#### IV. BEARING DESIGN AND ANALYSIS (TASK II)

The design of a rolling element bearing for operation in a cryogenic fluid requires an understanding of the significant design parameters and the interaction of the fluid properties with the bearing design.

Rolling element bearing life, fatigue as well as wear, is a function of the lubricating properties of the operating fluid. Effective lubrication depends upon the existence of a separating film in the bearing zones of contact. This separating film thickness is a function of viscosity. Since the viscosity of a cryogenic fluid is extremely low, it can be concluded that without another source of lubrication, metal-to-metal contact will exist. In cryogenic fluids, other than liquid fluorine, the practice has been to use ball separators made from materials that will provide solid lubrication. The most successful ball separators have been fabricated from materials containing polytetrafluorethylene (PTFE). The most common of these are Armalon (laminated glass cloth with PTFE binder) and cast PTFE with a filler added to improve material properties. As discussed earlier, nonmetallics can not survive in liquid fluorine at the high (100 fps, 30 mps) ball-cage rubbing velocities. Consequently, metal ball separators were necessary in the bearing design. Also, as discussed earlier, these metals were selected with the theory that they would provide solid lubrication in the form of metallic fluorides.

Even with some solid lubrication provided, it must be assumed that the separating film will be very thin and some surface asperities will contact. This metal-to-metal contact then results in relatively high tractive or tangential surface shear stresses that are directly proportional to the normal stresses. Results of research programs, conducted by both Tallian (Ref 5) and Skurka (Ref 6), wherein rolling contact bearing life was investigated as a function of the dimensionless ratio of lubricant film thickness to raceway surface finish, seem to agree that when metal-to-metal ball-race contact exists, fatigue life is reduced approximately 80%.

Experience has shown that wear and not fatigue establishes the usable life of rolling element bearing operating in cryogenic fluids with metal-to-metal contact. Since wear was of prime concern, it was desirable to minimize ball spin and microslip in the contact zone. This was accomplished by designing for outer race control and by incorporating a relatively open (wide) curvature on the inner race.

##### A. TASK I DESIGN

The bearing for the initial cage material evaluation tests, Task I, was not designed on this program. Existing 210 size bearing races and balls available as surplus from another NASA contract were utilized. A new ball separator was designed for these available bearings. All bearing elements were manufactured from Air Melt AISI 440c. Ball separators were designed to be fabricated from Berylco Nickel 440, HyMu 80, and Rene' 41.

#### IV, A, Task I Design (cont.)

The internal geometry of this bearing design is summarized below.

|                                    |                                        |
|------------------------------------|----------------------------------------|
| Ball complement, z                 | 12                                     |
| Ball dia, d                        | 0.50000 in. ( $1.27 \times 10^{-2}$ m) |
| Race curvatures                    |                                        |
| Outer, fo                          | 51%                                    |
| Inner, fi                          | 54%                                    |
| Unmounted contact angle, $\beta_o$ | 24°                                    |
| Class                              | ABEC 5                                 |
| Ball grade                         | AFBMA 10                               |

The following design philosophy was employed for the Task I ball separator design.

1. The ball separator was designed to be guided on the outer race lands. The bearing design race curvatures of 54% (fo) and 51% (fi) results in outer race ball control. Therefore, ball spinning occurred on the inner race and outer race guiding allowed more effective cooling of the inner race load zone.

2. The ball separator cross-section was held to a minimum with the requirement that full ball contact (wear ellipse) would still exist with a wear depth up to 0.010 in. ( $2.54 \times 10^{-5}$  m).

3. The operating clearance at the two outer race guiding lands was 0.007 to 0.009 in. ( $1.78 \times 10^{-6}$  to  $2.29 \times 10^{-6}$  m). This is slightly on the tight side of the recommended practices for conventional lubricated bearings, which is 0.003 in. ( $0.76 \times 10^{-6}$  m) per inch ( $2.54 \times 10^{-2}$  m) of guiding surface diameter or in the case 0.009 in. ( $2.29 \times 10^{-6}$  m). This clearance was selected to provide ridged centering of the separator. It was planned to increase this clearance if post test inspection indicated that a problem existed.

4. The ball to pocket operating clearance was 0.018 to 0.022 in. ( $4.57 \times 10^{-6}$  to  $5.59 \times 10^{-6}$  m). This was considered a minimum clearance based upon practical experience. This allowed material for increasing clearance if the bearing operating dynamics, determined by post test inspection, indicated that ball speed variations were subjecting the separator to undesirable force couples.

5. Ball separator design for the three materials (HyMu 80, Rene' 41, and Berylco Nickel 440) were identical.

#### IV, A, Task I Design (cont.)

6. A single piece design without the ball containment feature was selected for the ball separator to facilitate post test inspection of the wear surfaces. This design, shown in Figure 3, was possible only because the split inner race provided natural ball containment in the assembled state while permitting complete separability.

#### B. TASK II DESIGN

An analysis was conducted for the purpose of evolving an optimum design for the internal geometry of bearings for the Task IV and Task V bearing tests in liquid fluorine and FLOX. The following is the internal geometry of the optimized design.

|                                    |                                       |
|------------------------------------|---------------------------------------|
| Ball complement, z                 | 16                                    |
| Ball diameter, d                   | 0.4375 in. ( $1.11 \times 10^{-2}$ m) |
| Race curvatures                    |                                       |
| Outer, $f_o$                       | 52%                                   |
| Inner, $f_i$                       | 54%                                   |
| Unmounted contact angle, $\beta_o$ | 30°                                   |
| Class                              | ABEC 5                                |
| Ball grade                         | AFBMA 10                              |

This design was modified from the computer analysis based upon experience as well as practical considerations not programmed into a computer. From the computer output, it could be concluded that a 52% inner race curvature and a 35-degree contact angle would be more desirable because both of these changes would provide more axial load capacity. However, as illustrated on Figures 4 and 5, heat generation increases appreciably with both of these changes. Life decreases appreciably as inner race curvature decreases but is insensitive to a change in contact angle. Also the combination of a 52% outer and 54% inner will assure that ball control is maintained at the outer race.

It could also be concluded that larger balls would be desirable based upon the computer analysis showing that load capacity increases greatly while life becomes appreciably greater as ball diameter increases (see Figure 6). However, both heat generation and practical considerations influenced the selection of the 7/16-in. ( $1.11 \times 10^{-2}$  m) diameter ball size. As can be seen from Figure 6, heat generation increases appreciably with ball size. A practical ball diameter for a 210 size ball bearing is in the range of 7/16-in. to 1/2-in. ( $1.11 \times 10^{-2}$  to  $1.27 \times 10^{-2}$  m). Below this range, capacity is lost and above this range the races become too thin. Ball centrifugal force also must be considered. Figure 7 is a plot of centrifugal force for 7/16-in., 1/2-in., and 9/16-in. ( $1.11 \times 10^{-2}$ ,  $1.27 \times 10^{-2}$ , and  $1.43 \times 10^{-2}$  m) diameter balls of 440c material as a function of inner race rotational speed.



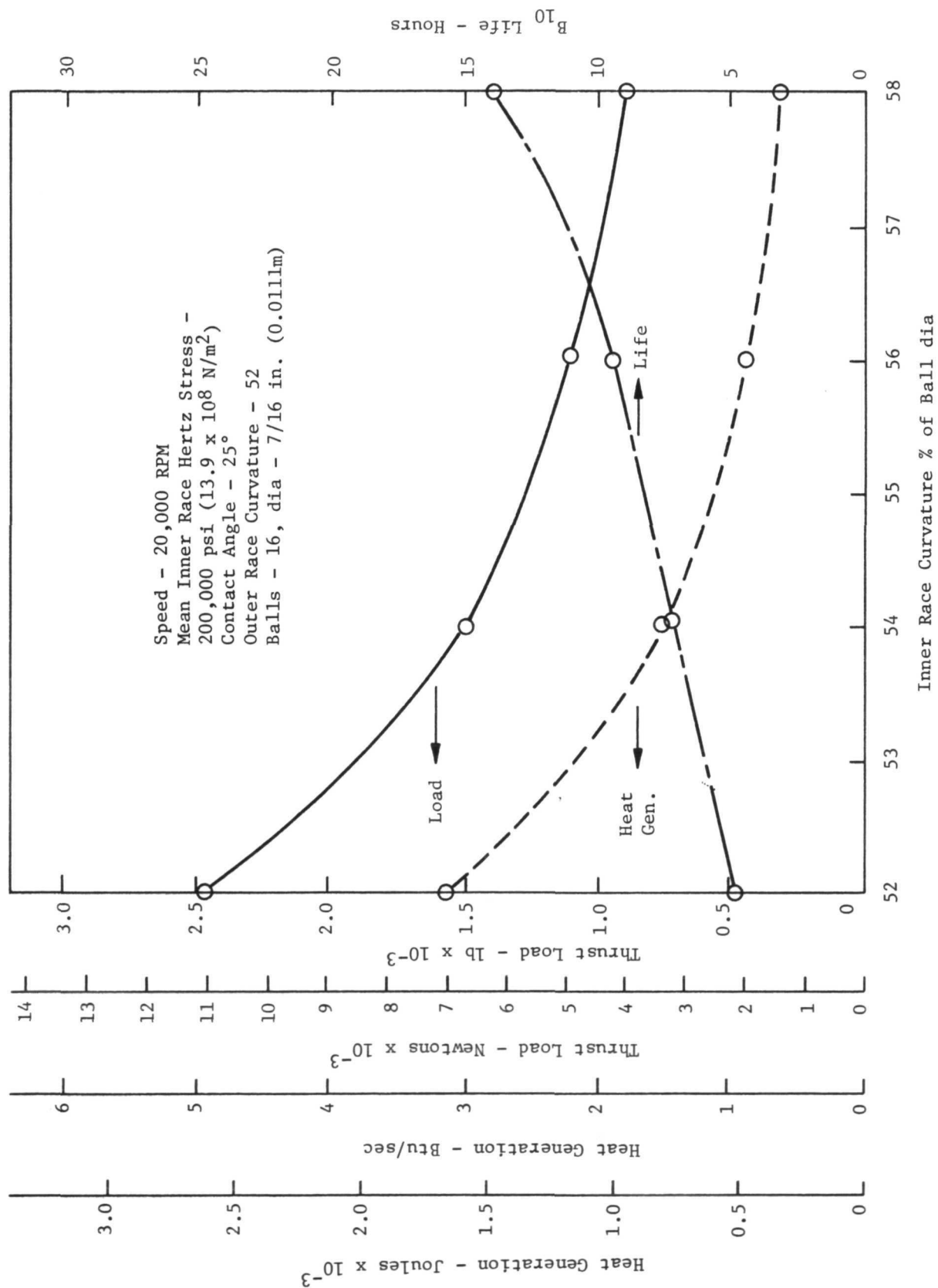


Figure 4. Inner Race Curvature vs Thrust Load, Heat Generation, and  $B_{10}$  Life



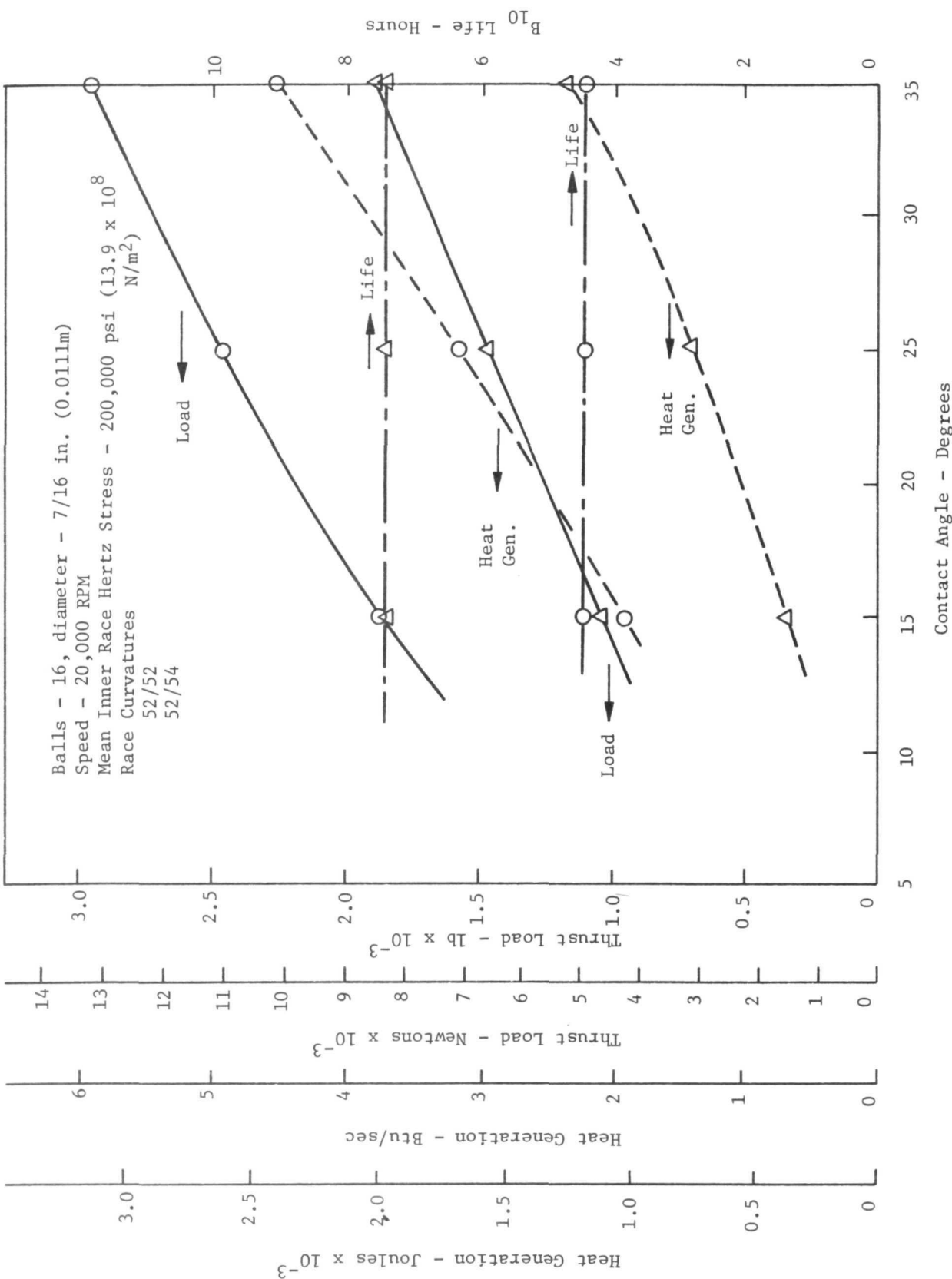


Figure 5. Contact Angle vs Thrust Load, Heat Generation, and B<sub>10</sub> Life



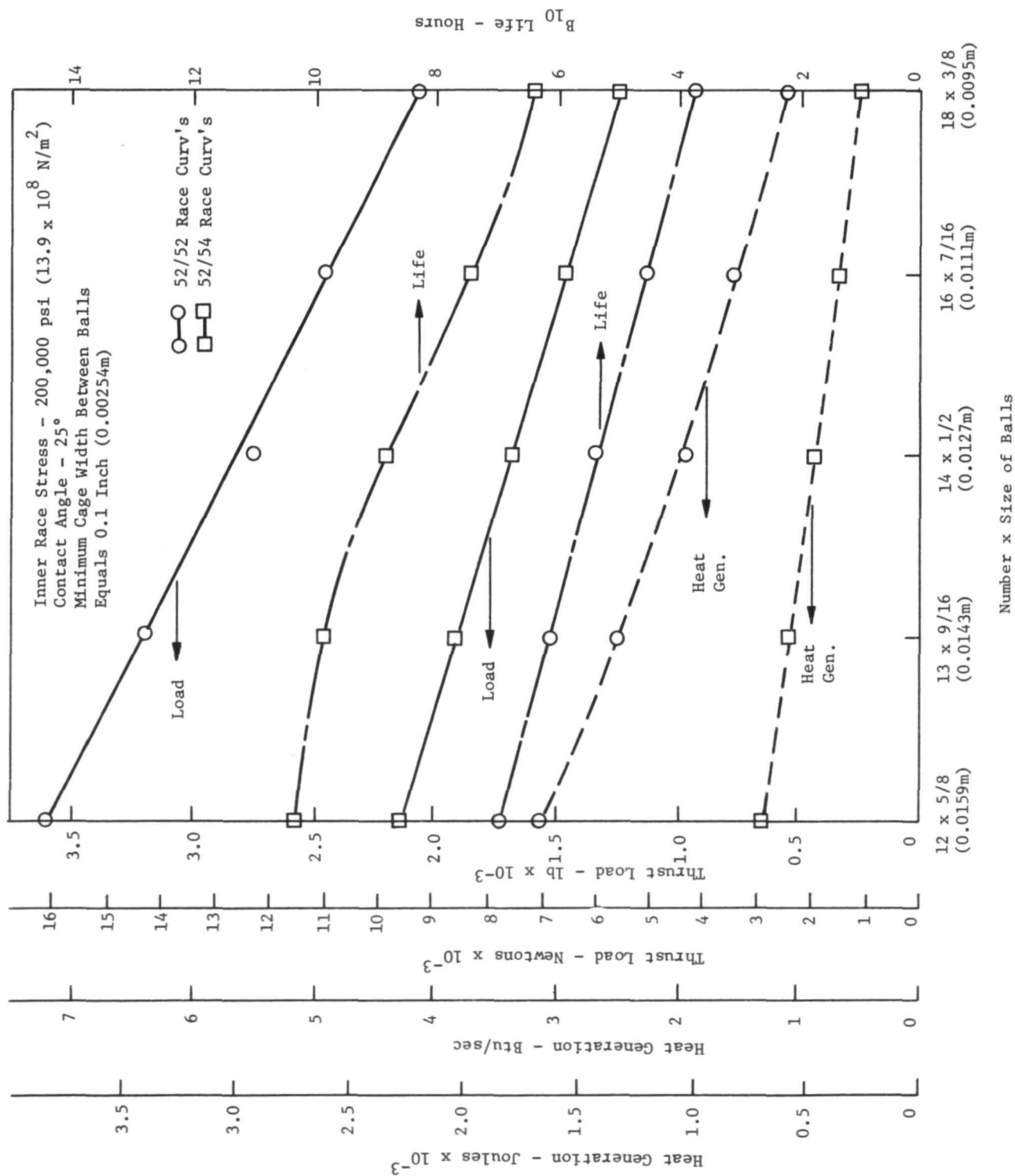


Figure 6. Number and Size of Balls vs Thrust Load, Heat Generation and  $B_{10}$  Life

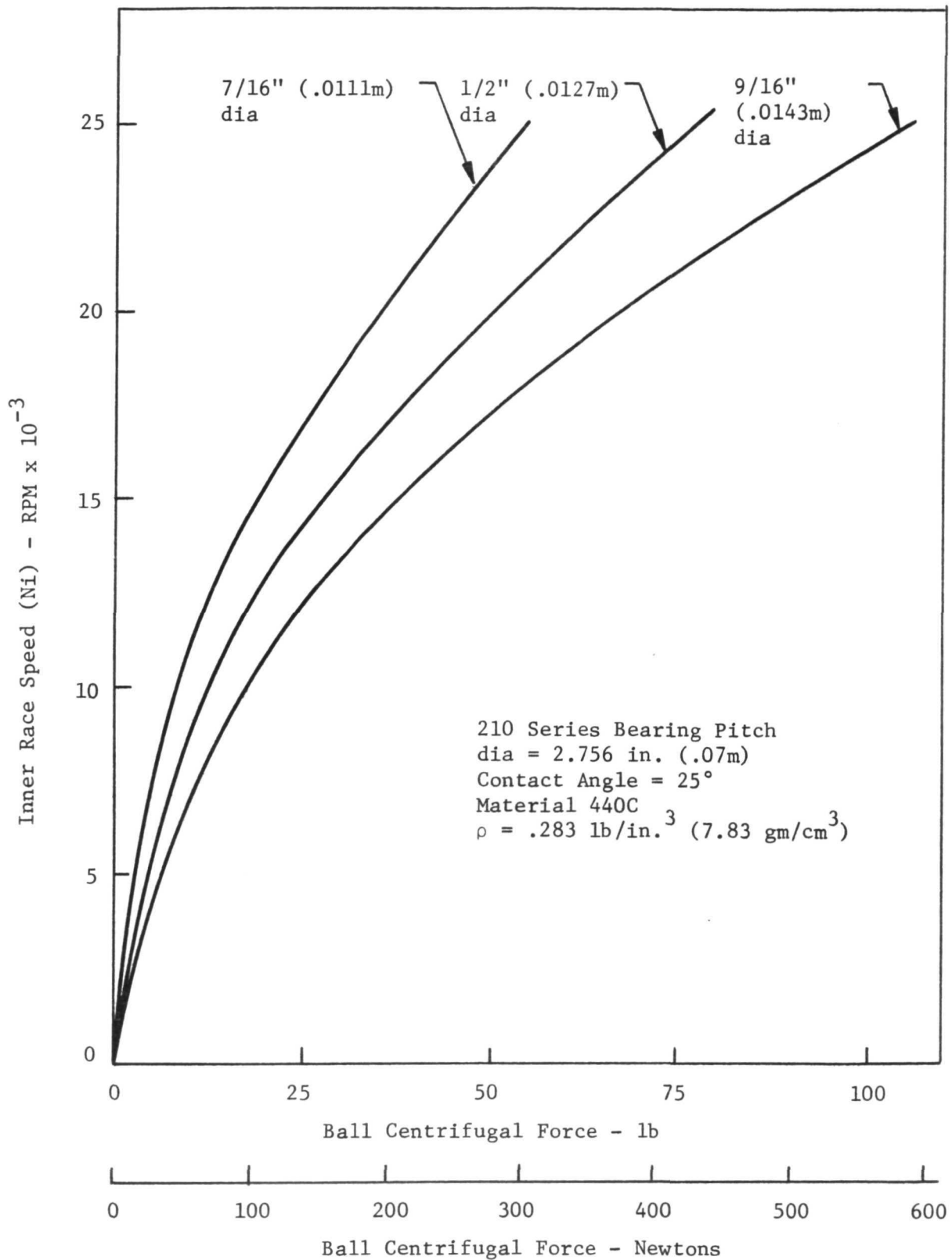


Figure 7. Centrifugal Ball Force vs Inner Race RPM

#### IV, B, Task II Design (cont.)

The surface finish of the balls and races are most important in boundary lubrication conditions because no fluid film separation can be expected which means that surface asperities will contact. High local stresses result under load. The true area of contact is so small that, following elastic deformation, the material yield stress is reached and local welding occurs. Moving one surface relative to the other shears the weld and surface wear occurs.

CEVM 440c material was specified in the design in order to minimize nonmetallic inclusions which could react with the fluorine.

Table V compares the operating dynamics of the Task I and Task II bearings at 20,000 rpm and 1160-lb (5160N) axial load. Note that the  $0.2 B_1$  life is higher for the Task II bearing. The 0.2 is a life multiplier used for operation without fluid film. This reduction factor is based upon the results of research programs, conducted by both Tallian (Ref 5) and Skurka (Ref 6) wherein rolling contact bearing life was investigated as a function of the dimensionless ratio  $\lambda$  (lubricant film thickness to raceway surface finish). Also, the friction torque--thus the heat generation--is slightly lower for the Task II bearing design. The ball separators for the optimized bearing followed the same design philosophy used in Task I. The land clearance was increased slightly to 0.008 to 0.012 in. ( $2.03 \times 10^{-6}$  to  $3.05 \times 10^{-6}$  m) to prevent cage/race interference from a wedged metallic chip as was thought to have occurred during Phase I testing. The land width also was increased slightly to provide a proportional increase in bearing surface to balance the increased cage centrifugal load. The ball pocket clearance was the same, 0.018 to 0.022 in. ( $4.57 \times 10^{-6}$  to  $5.59 \times 10^{-6}$  m). This design is shown in Figure 8. Materials selected are listed below. Table VI lists some of the mechanical properties of these materials.

1. Berylco Nickel 440 (annealed)
2. Rene' 41 (annealed)
3. HyMu 80 (annealed)
4. Berylco Nickel 440 coated with a mixture of 76% calcium fluoride and 24% lithium fluoride
5. Sintered Inco 600, 40% porosity and impregnated with a mixture of 76% calcium fluoride and 24% lithium fluoride
6. Sintered Inco 600, 40% porosity and impregnated with lithium fluoride

The first three materials were retained, since no elimination could be made during the Task I materials evaluation testing. The fourth material was selected on the basis of slider and bearing tests conducted by NASA at the Lewis Research Center (Ref 7 and 4). While most of these tests were performed

TABLE V

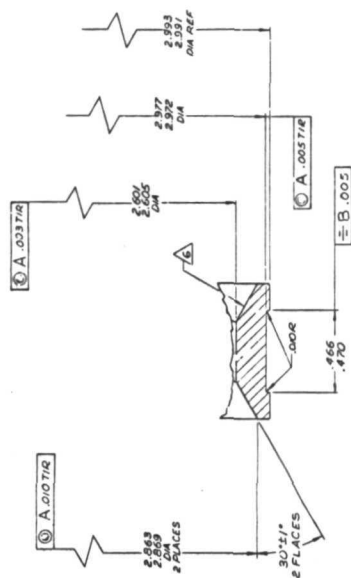
COMPARISON OF TASK I AND TASK II BEARING OPERATING  
DYNAMICS AT 20,000 RPM AND 5160 N AXIAL LOAD

|                                 | <u>TASK I DESIGN</u>             | <u>TASK II DESIGN</u>              |
|---------------------------------|----------------------------------|------------------------------------|
| Contact Angle                   |                                  |                                    |
| Outer, deg                      | 21.4                             | 24.7                               |
| Inner, deg                      | 29.1                             | 34.4                               |
| Pitch Dia, in. (cm)             | 2.7567 (7.0020)                  | 2.7571 (7.0030)                    |
| Contact Load                    |                                  |                                    |
| Outer, lb (N)                   | 245 (1,898)                      | 160 (1,172)                        |
| Inner, lb (N)                   | 199 (885.1)                      | 128 (569.4)                        |
| Ball Centrifugal Force, lb (N)  | 51.8 (230.4)                     | 37.2 (165.5)                       |
| Mean Hertz Stress               |                                  |                                    |
| Outer, psi (N/m <sup>2</sup> )  | 130,550 (90 x 10 <sup>7</sup> )  | 144,040 (99.3 x 10 <sup>7</sup> )  |
| Inner, psi (N/m <sup>2</sup> )  | 187,530 (129 x 10 <sup>7</sup> ) | 174,570 (120.4 x 10 <sup>7</sup> ) |
| 0.2 B <sub>1</sub> Life         |                                  |                                    |
| Outer, hr                       | 116                              | 52.4                               |
| Inner, hr                       | 4.6                              | 5.9                                |
| Bearing, hr                     | 4.5                              | 5.4                                |
| Gyroscopic Slip Coefficient     | 0.031                            | 0.039                              |
| Ball Spin Velocity              |                                  |                                    |
| Relative to Outer, RPM          | 0                                | 0                                  |
| Relative to Inner, RPM          | -15,936                          | -20,675                            |
| Ball Roll Velocity              |                                  |                                    |
| Relative to Outer, RPM          | -46,604                          | -55,176                            |
| Relative to Inner, RPM          | 63,665                           | 70,866                             |
| Ball Spin to Roll Ratio         |                                  |                                    |
| Rel. to Inner                   | 0.25                             | 0.29                               |
| Ball Spin Torque                |                                  |                                    |
| Relative to Outer, in-lb (cm-N) | 1.9 (21.5)                       | 0.79 (8.9)                         |
| Relative to Inner, in-lb (cm-N) | 0.87 (9.8)                       | 0.46 (5.2)                         |
| Ball Roll Torque                |                                  |                                    |
| Relative to Outer, in-lb (cm-N) | 0.13 (1.47)                      | 0.039 (0.44)                       |
| Relative to Inner, in-lb (cm-N) | 0.003 (0.034)                    | 0.016 (0.18)                       |

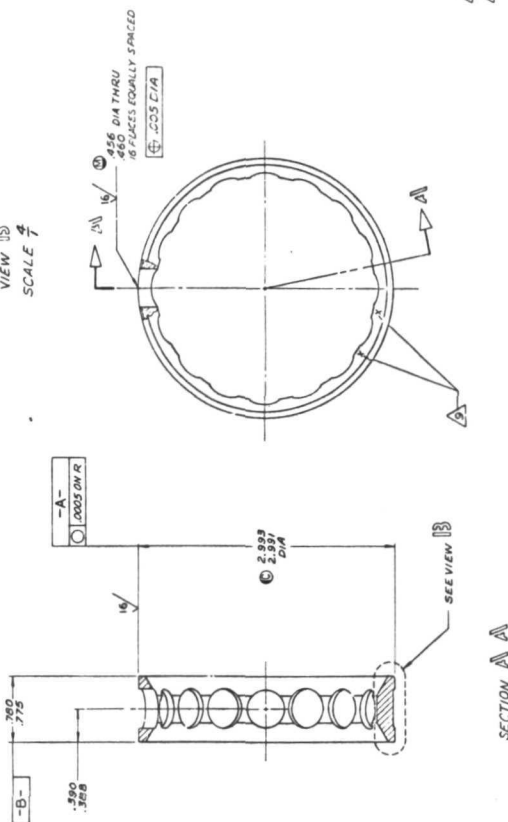
TABLE V (cont.)

|                                                                                         | <u>TASK I DESIGN</u>                        | <u>TASK II DESIGN</u>                       |
|-----------------------------------------------------------------------------------------|---------------------------------------------|---------------------------------------------|
| Bearing Friction Torque, in-lb (m-N)                                                    | 13.2 (149.0)<br>(Coeff. Friction<br>= 0.25) | 10.3 (116.5)<br>(Coeff. Friction<br>= 0.25) |
| Ball Orbital Velocity, RPM                                                              | 8,453                                       | 8,755                                       |
| Ball Rotational Velocity, RPM                                                           | -54,560                                     | -63,234                                     |
| Maximum SV Value<br>(Compressive Stress x Sliding<br>Velocity), psi x ft/sec, (N/m-sec) | 883,490 ( $18.567 \times 10^8$ )            | 879,180 ( $18.476 \times 10^8$ )            |

- |   |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
|---|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1 | REMOVE ALL "TS AND TYPING ERRORS EQUIVOCAL" TO "DUB" UNLESS GIVEN A 1A SYNCHRON.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
| 2 | INTERPRET "TS" FOR ALL Q-1000.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
| 3 | ALL PHYSICALS: SMALL APPLY AT $10^{-2}$ PER AC-STD-484.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
| 4 | CLASSIFICATION OF QUALITY CHARACTERISTICS PER AC-STD-484.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| 5 | SURFACE CHARACTERISTICS: 1A, 1B, 1C, 1D, 1E, 1F, 1G, 1H, 1I, 1J, 1K, 1L, 1M, 1N, 1O, 1P, 1Q, 1R, 1S, 1T, 1U, 1V, 1W, 1X, 1Y, 1Z, 1AA, 1AB, 1AC, 1AD, 1AE, 1AF, 1AG, 1AH, 1AI, 1AJ, 1AK, 1AL, 1AM, 1AN, 1AO, 1AP, 1AQ, 1AR, 1AS, 1AT, 1AU, 1AV, 1AW, 1AX, 1AY, 1AZ, 1BA, 1BB, 1BC, 1BD, 1BE, 1BF, 1BG, 1BH, 1BI, 1BJ, 1BK, 1BL, 1BM, 1BN, 1BO, 1BP, 1BQ, 1BR, 1BS, 1BT, 1BU, 1BV, 1BW, 1BX, 1BY, 1BZ, 1CA, 1CB, 1CC, 1CD, 1CE, 1CF, 1CG, 1CH, 1CI, 1CJ, 1CK, 1CL, 1CM, 1CN, 1CO, 1CP, 1CQ, 1CR, 1CS, 1CT, 1CU, 1CV, 1CW, 1CX, 1CY, 1CZ, 1DA, 1DB, 1DC, 1DD, 1DE, 1DF, 1DG, 1DH, 1DI, 1DJ, 1DK, 1DL, 1DM, 1DN, 1DO, 1DP, 1DQ, 1DR, 1DS, 1DT, 1DU, 1DV, 1DW, 1DX, 1DY, 1DZ, 1EA, 1EB, 1EC, 1ED, 1EE, 1EF, 1EG, 1EH, 1EI, 1EJ, 1EK, 1EL, 1EM, 1EN, 1EO, 1EP, 1EQ, 1ER, 1ES, 1ET, 1EU, 1EV, 1EW, 1EX, 1EY, 1EZ, 1FA, 1FB, 1FC, 1FD, 1FE, 1FF, 1FG, 1FH, 1FI, 1FJ, 1FK, 1FL, 1FM, 1FN, 1FO, 1FP, 1FQ, 1FR, 1FS, 1FT, 1FU, 1FV, 1FW, 1FX, 1FY, 1FZ, 1GA, 1GB, 1GC, 1GD, 1GE, 1GF, 1GG, 1GH, 1GI, 1GJ, 1GK, 1GL, 1GM, 1GN, 1GO, 1GP, 1GQ, 1GR, 1GS, 1GT, 1GU, 1GV, 1GW, 1GX, 1GY, 1GZ, 1HA, 1HB, 1HC, 1HD, 1HE, 1HF, 1HG, 1HH, 1HI, 1HJ, 1HK, 1HL, 1HM, 1HN, 1HO, 1HP, 1HQ, 1HR, 1HS, 1HT, 1HU, 1HV, 1HW, 1HX, 1HY, 1HZ, 1IA, 1IB, 1IC, 1ID, 1IE, 1IF, 1IG, 1IH, 1II, 1IJ, 1IK, 1IL, 1IM, 1IN, 1IO, 1IP, 1IQ, 1IR, 1IS, 1IT, 1IU, 1IV, 1IW, 1IX, 1IY, 1IZ, 1JA, 1JB, 1JC, 1JD, 1JE, 1JF, 1JG, 1JH, 1JI, 1JJ, 1JK, 1JL, 1JM, 1JN, 1JO, 1JP, 1JQ, 1JR, 1JS, 1JT, 1JU, 1JV, 1JW, 1JX, 1JY, 1JZ, 1KA, 1KB, 1KC, 1KD, 1KE, 1KF, 1KG, 1KH, 1KI, 1KJ, 1KK, 1KL, 1KM, 1KN, 1KO, 1KP, 1KQ, 1KR, 1KS, 1KT, 1KU, 1KV, 1KW, 1KX, 1KY, 1KZ, 1LA, 1LB, 1LC, 1LD, 1LE, 1LF, 1LG, 1LH, 1LI, 1LJ, 1LK, 1LL, 1LM, 1LN, 1LO, 1LP, 1LQ, 1LR, 1LS, 1LT, 1LU, 1LV, 1LW, 1LX, 1LY, 1LZ, 1MA, 1MB, 1MC, 1MD, 1ME, 1MF, 1MG, 1MH, 1MI, 1MJ, 1MK, 1ML, 1MM, 1MN, 1MO, 1MP, 1MQ, 1MR, 1MS, 1MT, 1MU, 1MV, 1MW, 1MX, 1MY, 1MZ, 1NA, 1NB, 1NC, 1ND, 1NE, 1NF, 1NG, 1NH, 1NI, 1NJ, 1NK, 1NL, 1NM, 1NN, 1NO, 1NP, 1NQ, 1NR, 1NS, 1NT, 1NU, 1NV, 1NW, 1NX, 1NY, 1NZ, 1OA, 1OB, 1OC, 1OD, 1OE, 1OF, 1OG, 1OH, 1OI, 1OJ, 1OK, 1OL, 1OM, 1ON, 1OO, 1OP, 1OQ, 1OR, 1OS, 1OT, 1OU, 1OV, 1OW, 1OX, 1OY, 1OZ, 1PA, 1PB, 1PC, 1PD, 1PE, 1PF, 1PG, 1PH, 1PI, 1PJ, 1PK, 1PL, 1PM, 1PN, 1PO, 1PP, 1PQ, 1PR, 1PS, 1PT, 1PU, 1PV, 1PW, 1PX, 1PY, 1PZ, 1QA, 1QB, 1QC, 1QD, 1QE, 1QF, 1QG, 1QH, 1QI, 1QJ, 1QK, 1QL, 1QM, 1QN, 1QO, 1QP, 1QQ, 1QR, 1QS, 1QT, 1QU, 1QV, 1QW, 1QX, 1QY, 1QZ, 1RA, 1RB, 1RC, 1RD, 1RE, 1RF, 1RG, 1RH, 1RI, 1RJ, 1RK, 1RL, 1RM, 1RN, 1RO, 1RP, 1RQ, 1RR, 1RS, 1RT, 1RU, 1RV, 1RW, 1RX, 1RY, 1RZ, 1SA, 1SB, 1SC, 1SD, 1SE, 1SF, 1SG, 1SH, 1SI, 1SJ, 1SK, 1SL, 1SM, 1SN, 1SO, 1SP, 1SQ, 1SR, 1SS, 1ST, 1SU, 1SV, 1SW, 1SX, 1SY, 1SZ, 1TA, 1TB, 1TC, 1TD, 1TE, 1TF, 1TG, 1TH, 1TI, 1TJ, 1TK, 1TL, 1TM, 1TN, 1TO, 1TP, 1TQ, 1TR, 1TS, 1TT, 1TU, 1TV, 1TW, 1TX, 1TY, 1TZ, 1UA, 1UB, 1UC, 1UD, 1UE, 1UF, 1UG, 1UH, 1UI, 1UJ, 1UK, 1UL, 1UM, 1UN, 1UO, 1UP, 1UQ, 1UR, 1US, 1UT, 1UU, 1UV, 1UW, 1UX, 1UY, 1UZ, 1VA, 1VB, 1VC, 1VD, 1VE, 1VF, 1VG, 1VH, 1VI, 1VJ, 1VK, 1VL, 1VM, 1VN, 1VO, 1VP, 1VQ, 1VR, 1VS, 1VT, 1VU, 1VV, 1VW, 1VX, 1VY, 1VZ, 1WA, 1WB, 1WC, 1WD, 1WE, 1WF, 1WG, 1WH, 1WI, 1WJ, 1WK, 1WL, 1WM, 1WN, 1WO, 1WP, 1WQ, 1WR, 1WS, 1WT, 1WU, 1WV, 1WW, 1WX, 1WY, 1WZ, 1XA, 1XB, 1XC, 1XD, 1XE, 1XF, 1XG, 1XH, 1XI, 1XJ, 1XK, 1XL, 1XM, 1XN, 1XO, 1XP, 1XQ, 1XR, 1XS, 1XT, 1XU, 1XV, 1XW, 1XX, 1XY, 1XZ, 1YA, 1YB, 1YC, 1YD, 1YE, 1YF, 1YG, 1YH, 1YI, 1YJ, 1YK, 1YL, 1YM, 1YN, 1YO, 1YP, 1YQ, 1YR, 1YS, 1YT, 1YU, 1YV, 1YW, 1YX, 1YY, 1YZ, 1ZA, 1ZB, 1ZC, 1ZD, 1ZE, 1ZF, 1ZG, 1ZH, 1ZI, 1ZJ, 1ZK, 1ZL, 1ZM, 1ZN, 1ZO, 1ZP, 1ZQ, 1ZR, 1ZS, 1ZT, 1ZU, 1ZV, 1ZW, 1ZX, 1ZY, 1ZZ, 1AAA, 1AAB, 1AAC, 1AAD, 1AAE, 1AAF, 1AAG, 1AAH, 1AAI, 1AAJ, 1AAK, 1AAL, 1AAM, 1AAN, 1AAO, 1AAP, 1AAQ, 1AAR, 1AAS, 1AAT, 1AAU, 1AAV, 1AAW, 1AAX, 1AAY, 1AAZ, 1ABA, 1ABB, 1ABC, 1ABD, 1ABE, 1ABF, 1ABG, 1ABH, 1ABI, 1ABJ, 1ABK, 1ABL, 1ABM, 1ABN, 1ABO, 1ABP, 1ABQ, 1ABR, 1ABS, 1ABT, 1ABU, 1ABV, 1ABW, 1ABX, 1ABY, 1ABZ, 1ABA, 1ABB, 1ABC, 1ABD, 1ABE, 1ABF, 1ABG, 1ABH, 1ABI, 1ABJ, 1ABK, 1ABL, 1ABM, 1ABN, 1ABO, 1ABP, 1ABQ, 1ABR, 1ABS, 1ABT, 1ABU, 1ABV, 1ABW, 1ABX, 1ABY, 1ABZ, 1ACA, 1ACB, 1ACC, 1ACD, 1ACE, 1ACF, 1ACG, 1ACH, 1ACI, 1ACJ, 1ACK, 1ACL, 1ACM, 1ACN, 1ACO, 1ACP, 1ACQ, 1ACR, 1ACS, 1ACT, 1ACU, 1ACV, 1ACW, 1ACX, 1ACY, 1ACZ, 1ACA, 1ACB, 1ACC, 1ACD, 1ACE, 1ACF, 1ACG, 1ACH, 1ACI, 1ACJ, 1ACK, 1ACL, 1ACM, 1ACN, 1ACO, 1ACP, 1ACQ, 1ACR, 1ACS, 1ACT, 1ACU, 1ACV, 1ACW, 1ACX, 1ACY, 1ACZ, 1ADA, 1ADB, 1ADC, 1ADD, 1ADE, 1ADF, 1ADG, 1ADH, 1ADI, 1ADJ, 1ADK, 1ADL, 1ADM, 1ADN, 1ADO, 1ADP, 1ADQ, 1ADR, 1ADS, 1ADT, 1ADU, 1ADV, 1ADW, 1ADX, 1ADY, 1ADZ, 1ADA, 1ADB, 1ADC, 1ADD, 1ADE, 1ADF, 1ADG, 1ADH, 1ADI, 1ADJ, 1ADK, 1ADL, 1ADM, 1ADN, 1ADO, 1ADP, 1ADQ, 1ADR, 1ADS, 1ADT, 1ADU, 1ADV, 1ADW, 1ADX, 1ADY, 1ADZ, 1AEA, 1AEB, 1AEC, 1AED, 1AEE, 1AEF, 1AEG, 1AEH, 1AEI, 1AEJ, 1AEK, 1AEL, 1AEM, 1AEN, 1AEO, 1AEP, 1AEQ, 1AER, 1AES, 1AET, 1AEU, 1AEV, 1AEW, 1AEX, 1AEY, 1AEZ, 1AEA, 1AEB, 1AEC |



VIEW 13  
SCALE  $\frac{4}{1}$



SECTION 44.41

| QTY | UNIT | DESCRIPTION                 | DATE | TIME | INITIALS | REMARKS |
|-----|------|-----------------------------|------|------|----------|---------|
| 1   | EA   | MAKE F/C - 115735-E         | -5   |      |          |         |
| 1   | EA   | MAKE F/C 115735-E           | -4   |      |          |         |
| 1   | EA   | NYM400                      | -3   |      |          | 7421    |
| 1   | EA   | RENE 41 51'S                | -2   |      |          |         |
| 1   | EA   | BERYLCO NICKEL 440 ANNEALED | -1   |      |          | 7403    |
| 1   | EA   | INITIAL DATE OF TIME        |      |      |          |         |

| QTY | UNIT | DESCRIPTION            | DATE | TIME | INITIALS | REMARKS |
|-----|------|------------------------|------|------|----------|---------|
| 1   | EA   | RETAINER, BALL BEARING |      |      |          |         |
| 1   | EA   | 115737                 |      |      |          |         |

Figure 8. Task II Ball Separator Design

TABLE VI  
TYPICAL MECHANICAL PROPERTIES  
OF CAGE MATERIALS

| Material                         | Ultimate<br>Strength<br>(ksi) | 2% Offset<br>Yield Strength<br>(ksi) | Elongation<br>(%) | Reduction<br>in Area<br>(%) | Hardness<br>Rockwell |
|----------------------------------|-------------------------------|--------------------------------------|-------------------|-----------------------------|----------------------|
| Berylco Nickel 440<br>(Annealed) | 95                            | 40                                   | 40                | 45                          | B-70                 |
| Rene' 41<br>(Annealed)           | 120                           | 80                                   | 35                |                             | C-24                 |
| HyMu 60<br>(Annealed)            | 80                            | 22                                   | 60                | 70                          | B-60                 |
| Inco 600<br>(Annealed)           | 100                           | 44                                   | 45                | 50                          | B-75                 |

#### IV, B, Task II Design (cont.)

in other environments (air, gaseous hydrogen, vacuum, and liquid sodium) and at elevated temperatures, a few were conducted in liquid fluorine and liquid oxygen (Ref 4). The fluoride-impregnated Inco 600 materials were selected primarily because the existence of the lubricating fluorides would not be time dependent on the rate of fluorine-cage reaction. Their potential adequacy as a cage material also had been successfully demonstrated by elevated temperature bearing tests at the Lewis Research Center (Ref 8). The composite ball separators were inner ring riding and exhibited adequate strength even at elevated temperatures. However, the speeds tested--2000 and 4000 rpm--were considerably lower than the 20,000 rpm required by this program. Hoop stress for a separator of this material was calculated to be 3080 psi ( $2.12 \times 10^6$  N/m<sup>2</sup>) at 20,000 rpm. To assure adequate strength a safety factor of 2 was used and each infiltrated blank was required to survive two  $110 \pm 10$ -lb ( $489 \pm 44.5$ N) load tests 90° apart.

Total clearance in a ball separator (land plus ball pocket) must be sufficient to allow for ball speed variations (BSV) which can result in high separator loading. Without BSV the rotational speed of the separator is the same as the ball orbit velocity.

The equation for the orbiting speed of a ball is:

$$n = 1/2 N_i [1 - (d/E) \cos \beta_i]$$

Where:

- $n$  = ball orbital velocity, rpm
- $N_i$  = inner race speed, rpm
- $d$  = ball diameter, in. (0.02254 m)
- $E$  = pitch diameter, in. (0.02254 m)
- $\beta_i$  = inner race contact angle, deg

For a perfect bearing, precisely aligned and operating under a pure thrust load, the orbital velocity of each ball is identical and ball speed will not vary. However, in actual practice, various bearing imperfections exist and the applied load will include a radial component. Since  $d$ ,  $E$ , and  $\cos \beta_i$  can all vary, it is obvious from the previous equation that  $n$  is not identical for all balls and that some BSV will occur. Smaller than nominal size balls will operate at larger than nominal contact angle and orbital speed; larger balls will operate in a similar manner but at lower than the nominal values of these parameters. When BSV is caused by a radial load component or ovality of the races, each ball will advance and retard an equal amount during one revolution. Cage-pocket-to-ball forces will, therefore, remain constant, provided that sufficient pocket clearance has been provided. When BSV occurs because of ball size differences, the undersize balls will advance continuously



#### IV, B, Task II Design (cont.)

(the oversized balls will lag), resulting in a continuously changing index between balls and cage pocket loading, as shown in Figure 9. Since the ball displacements resulting from ball size variation are accumulative, and since the cages used on this program were rigid, the balls had to skid and slide on the races. This situation results in more ball wear and, therefore, more ball speed variations because of differential ball wear.

Cage/ball wear caused by ball size variation in bearings under constant thrust load cannot be alleviated simply by enlarging the ball pocket clearance. Either the lubrication must be enhanced to reduce tractive forces or the bearing geometry must include provisions to compensate for the accumulative ball displacement. Lubrication was considered fixed by definition since material evaluation was the intent of the program. Therefore, an inner race local relief (an unloading chute) similar to that used in Reference 9, was incorporated in the design. The operation of this feature, shown in Figure 10, may be described as follows: As each ball enters the unloading chute, the normal load (and tractive force between ball and race) is removed because of the increased clearance at the relief. Fluid friction causes the ball to slow down after which the back side of its cage pocket "kicks" the ball back into orbit at a speed approximately equal to the cage velocity.

The center of the inner race relief was set at  $30^\circ$  (unmounted) to agree with the mounted contact angle at 20,000 rpm with 1000 lb (4448N) axial load. This load angle ( $\beta_1$ ) changes with ball wear due to the increased internal clearance and is tabulated in Figure 10 as a function of the change in ball diameter. From this tabulation it can be seen that the effectiveness of the unloading chute would be limited to small amounts of ball wear because any large amount of contact angle variation would allow the ball to "track" around the relief without the interrupting effect.

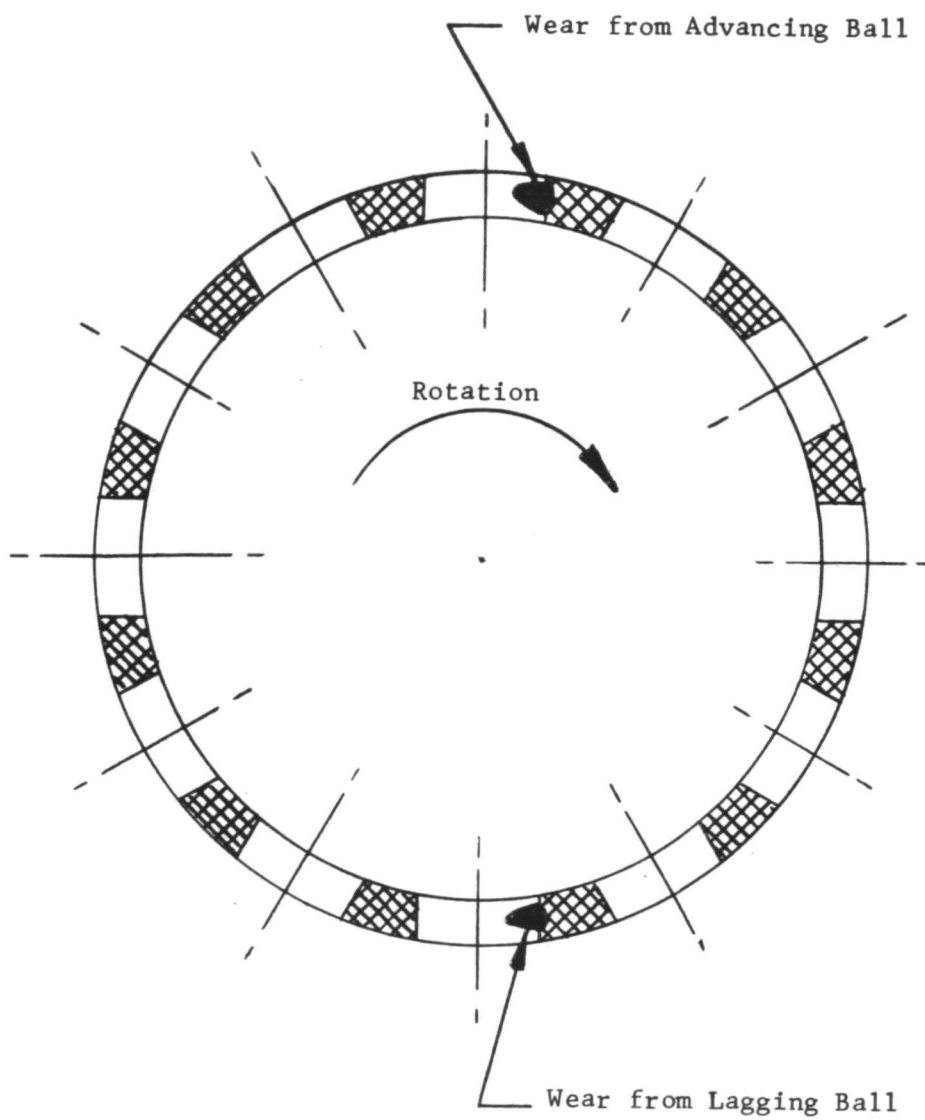


Figure 9. Cage Pocket Loading from Ball Size Differences

Operating Inner Race  
Contact Angle vs. Ball Wear

| $\Delta d/1000$ | $\beta_i$  |
|-----------------|------------|
| 0               | $34^\circ$ |
| 2               | $42^\circ$ |
| 4               | $48^\circ$ |
| 6               | $52^\circ$ |
| 8               | $56^\circ$ |
| 10              | $60^\circ$ |

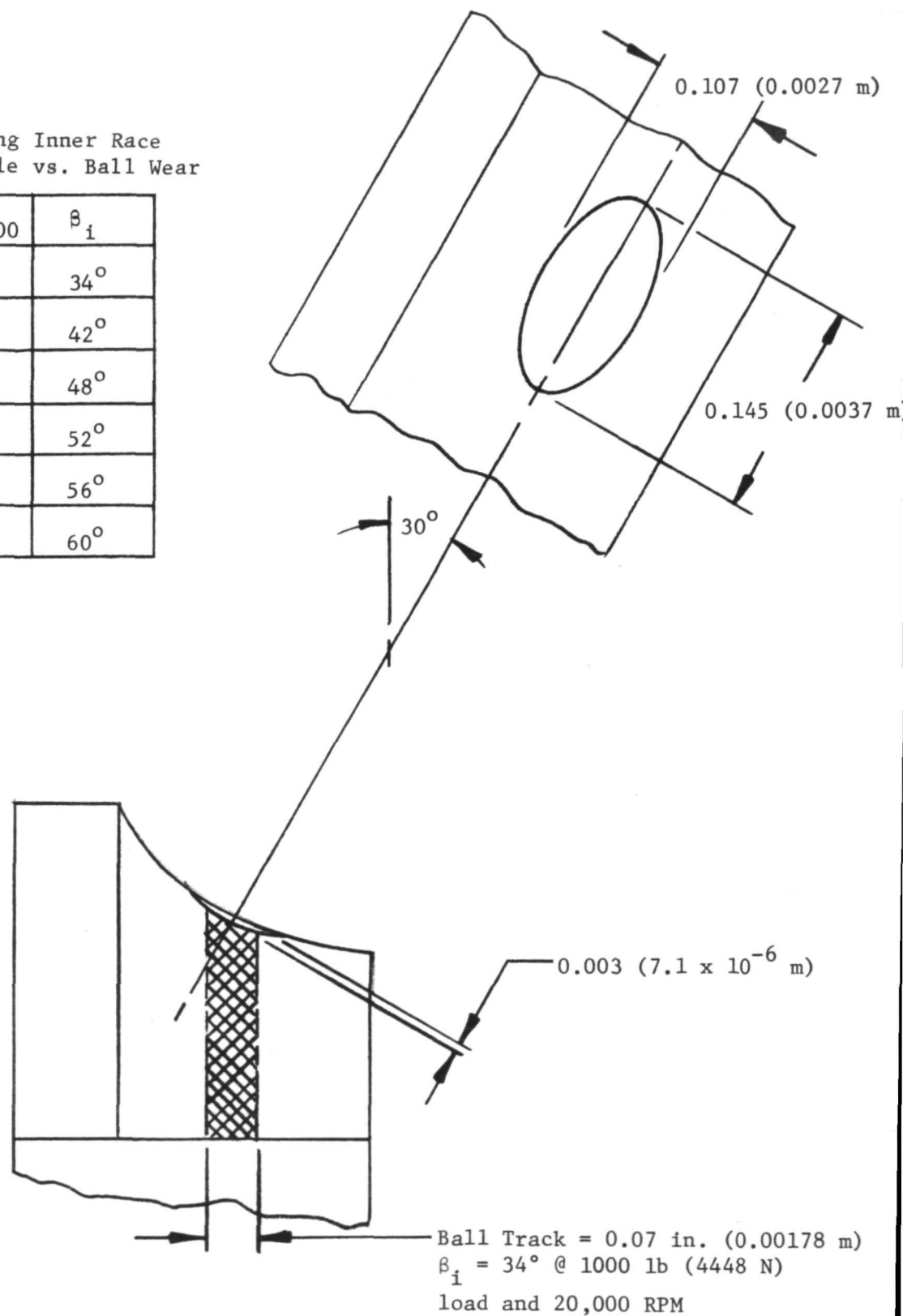


Figure 10. Inner Raceway Ball Unloading Chute Configuration

## V. BEARING COMPONENT FABRICATION

Task I ball separators were fabricated from Berylco Nickel 440, HyMu 80, and Rene' 41. Maintaining roundness of the separator outside diameter proved to be a problem to the vendor. One rework cycle was required in order to obtain uniform pieces. Figure 11 shows a typical talyrond inspection reading before and after rework. Roundness of this guiding surface was controlled more rigidly than usual so as to insure that the articles for the comparative material evaluation program were completely uniform. Successful operation has been reported (Ref 7) with ball separators that were as much as 0.047 in. ( $11.9 \times 10^{-4}$  m) out of round. Also shown on Figure 11 is a talyrond recording of the roundness after a liquid nitrogen soak test. This soak test was performed to insure that dimensional stability of the parts at cryogenic temperature. As can be seen, there was no dimensional change.

The Task II ball bearing rings and balls were fabricated from CEVM material. In order to have pretest dimensions certified, inspection records were a purchase order requirement. Sufficient inspection was performed to verify the validity of these records.

No major problems were experienced in the fabrication of the Task II ball separators. Again the vendors were required to deliver certified inspection records. All blanks of the impregnated Inco 600 survived the required load testing. The Berylco Nickel 440 separators that were scheduled for the fused coating of the calcium fluoride and lithium fluoride mixture were machined 0.002 in. ( $5.08 \times 10^{-4}$  m) undersize on all dimensions. This coating was applied at NASA Lewis Research Center and is reported in Reference 10.

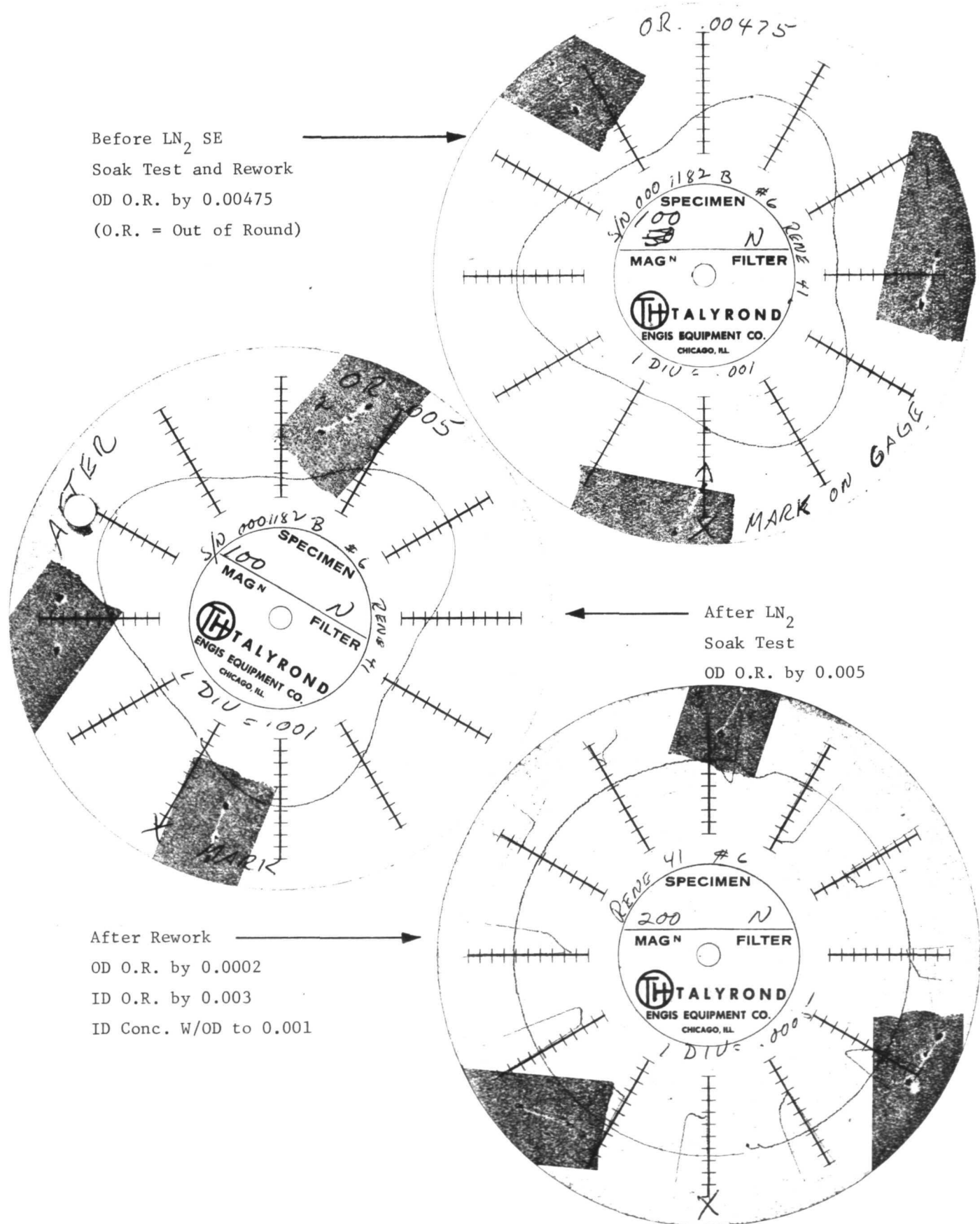


Figure 11. Tallyrond Inspection Record of Task I Separator

## VI. ONE-HOUR BEARING EVALUATION TESTS IN LIQUID FLUORINE - TASK IV

Twenty-three tests were conducted in this task. The initial test plan called for 18 tests. This plan consisted of three tests, each one hour in duration, on the six ball separators fabricated in Task III. The first three separator materials, Berylco Nickel 440, HyMu 80, and Rene' 41, were previously evaluated in the Task I material evaluation. Steady-state data for all Task IV tests are tabulated in Table VII. As noted in this table, 13 of the 23 tests went the full one-hour scheduled duration. Rotative speed was 20,000 rpm for all tests. Except for the first two tests, the applied axial load was set at  $\approx$  800 lb (3558N) on the upstream bearing and  $\approx$  1000 lb (4448N) on the downstream bearing.

Increasing axial play resulting from bearing ball wear allowed the load piston to bottom out on the bearing carrier in the first nine tests. This resulted in the loss of all load on the upstream bearing and reduction of the downstream bearing load from 1000 to 200 lb (4448 to 890N). After the ninth test, the load piston was reworked to prevent bottoming. The original design and the rework are shown in Figure 12. This loss of load resulted in shaft gyrations which resulted in tester shaft to labyrinth rubbing. Consequently, the wear data from these first nine tests can not be correlated directly with the subsequent constant load tests.

The last six tests incorporated a ball unloading chute in the inner raceway. The unloading chute configuration was tested in an attempt to reduce ball wear by breaking up the ball speed variations and reorienting each ball one each orbit revolution. The unloading chute design and a more complete discussion of the theory was given in Section IV, Bearing Design and Analysis. Figure 10 of that section shows the configuration. Two cage materials--LiF-impregnated Inco 600 and Berylco Nickel 440--were selected for these six tests. The LiF-impregnated Inco 600 was selected since ball wear was less with this material during previous testing ( $\approx$  0.004 in. ( $1.02 \times 10^{-4}$  m) as compared to  $\approx$  0.008 in. ( $2.04 \times 10^{-4}$  m) with other materials). The Berylco Nickel 440 was selected to provide two data samples for comparison with the results of the one-hour tests without unloading chutes. Two LiF-impregnated ball separators failed during these tests. The failures consisted of a single axial fracture across one ball pocket. These occurred in Test 22 after 35 minutes and in Test 25 after 55 minutes of the scheduled one-hour duration. Figure 13 is a photograph of the failed separator from Test 22. In both cases, increased torque in the bearing caused the speed to drop and the bearing temperature to rise. The testing device was shut down without further bearing damage. Another test with LiF-impregnated ball separators and ball unloading chutes (Test 26) went the hour duration without incident. It was concluded that material strength might have been borderline with respect to the repetitive shock loads it was subjected to with the ball unloading chute. The ball unloading chute did not reduce ball wear and the plan to test this configuration in FLOX was dropped.

Posttest inspection measurements from all Task IV tests are given in Section IX, Data Analysis, along with a discussion of the test results.

TABLE VII

TASK IV ONE-HOUR DURATION TESTS IN  
LIQUID FLUORINE STEADY-STATE DATA

| Test No. | Separator Material                                                        | Date    | Duration, min | Speed, RPM | LP <sub>2</sub> Flow, gpm (m <sup>3</sup> /min) | Axial Load                            |                                                           | Temperatures                  |                          |                            |                              | Remarks                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
|----------|---------------------------------------------------------------------------|---------|---------------|------------|-------------------------------------------------|---------------------------------------|-----------------------------------------------------------|-------------------------------|--------------------------|----------------------------|------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|          |                                                                           |         |               |            |                                                 | Upstream Bearing, lb <sub>f</sub> (K) | Downstream Bearing, lb <sub>f</sub> (m <sup>3</sup> /min) | LP <sub>2</sub> Inlet, °R (K) | Upstream Bearing, °R (K) | Downstream Bearing, °R (K) | LP <sub>2</sub> Exit, °R (K) |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| 1        | RyMu 80                                                                   | 3/23/70 | 60            | 20,000     | 17.0 (.0643)                                    | --                                    | --                                                        | 170 (94)                      | 172 (96)                 | 181 (101)                  | 180 (100)                    | Shaft to labyrinth seal rub occurred during test. The initial applied loads were 900 lb (4003 N) and 1200 lb (5338 N) on the upstream and downstream bearings respectively. Load was lost during the run due to bearing wear allowing axial movement and bottoming out of the load piston. This problem was not discovered until after test 11.                                                                                                                                                                             |
| 2        | Berylico Nickel 440 coated with fused mixture of LiF and CaF <sub>2</sub> | 3/31/70 | 60            | 20,000     | 17.0 (.0643)                                    | --                                    | --                                                        | 168 (93)                      | 171 (95)                 | 183 (102)                  | 171 (95)                     | Same remarks as test 1.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
| 3        | Berylico Nickel 440                                                       | 4/1/70  | 60            | 20,000     | 16.5 (.0624)                                    | --                                    | --                                                        | 168 (93)                      | 168 (93)                 | 179 (99)                   | 170 (94)                     | Same remarks as test 1, except the initial loads were 690 lb (3069 N) and 960 lb (4270 N) on the up and downstream bearings.                                                                                                                                                                                                                                                                                                                                                                                                |
| 4        | Rene' 41                                                                  | 4/2/70  | 60            | 20,000     | 16.5 (.0624)                                    | --                                    | --                                                        | 169 (94)                      | 179 (99)                 | 187 (104)                  | 173 (96)                     | Same remarks as test 1, except the initial loads were 760 lb (3380 N) and 1030 lb (4581 N).                                                                                                                                                                                                                                                                                                                                                                                                                                 |
| 5        | Inco 600 with impregnate of LiF and CaF <sub>2</sub> mixture              | 4/3/70  | 30            | 20,000     | 16.5 (.0624)                                    | --                                    | --                                                        | 176 (98)                      | 177 (98)                 | 190 (106)                  | --                           | Same remarks as test 1, except the initial loads were 820 lb (3647 N) and 1030 lb (4581 N). In an attempt to stop the labyrinth rubs the tester was disassembled and rewired to incorporate axial preload springs on the trunion bearings. Two checkout tests, 6 and 7, were conducted in liquid nitrogen prior to resumption of testing in LP <sub>2</sub> . Task 1 bearings with Armalyn separators were used for these tests. Both of these tests were smooth with no vibration, and no shaft to labyrinth rub occurred. |

TABLE VII (Cont.)

| Test No. | Separator Material                                                         | Date    | Duration, min | Speed, RPM | LP <sub>2</sub> Flow, gpm (m <sup>3</sup> /min) | Axial Load                            |                                                           | Temperatures                  |                          |                            | Remarks   |                                                                                                                                                                                                                                                                                                                                                                                                                                             |
|----------|----------------------------------------------------------------------------|---------|---------------|------------|-------------------------------------------------|---------------------------------------|-----------------------------------------------------------|-------------------------------|--------------------------|----------------------------|-----------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|          |                                                                            |         |               |            |                                                 | Upstream Bearing, lb <sub>f</sub> (N) | Downstream Bearing, lb <sub>f</sub> (m <sup>3</sup> /min) | LP <sub>2</sub> Inlet, °R (K) | Upstream Bearing, °R (K) | Downstream Bearing, °R (K) |           | LP <sub>2</sub> Exit, °R (K)                                                                                                                                                                                                                                                                                                                                                                                                                |
| 8        | Inco 600 with impregnate of LiF                                            | 8/6/70  | 60            | 20,000     | 16.0 (.0606)                                    | --                                    | --                                                        | 165 (92)                      | 168 (93)                 | 181 (101)                  | 170 (94)  | Shaft to labyrinth rub problem still existed due to loss of load. Initial loads were 810 lb (3603 N) and 1000 lb (4448 N).                                                                                                                                                                                                                                                                                                                  |
| 9        | Rene 41                                                                    | 8/7/70  | 7             | 20,000     | 10.5 (.0397)                                    | --                                    | --                                                        | 155 (86)                      | 181 (101)                | 186 (103)                  | --        | Premature shutdown due to high vibration, shaft displacement and labyrinth gub. The initial loads were 400 lb (1779 N) and 530 lb (2357 N). They were increased to 810 lb (3603 N) and 1000 lb (4448 N) just prior to shutdown.                                                                                                                                                                                                             |
| 10       | Berylco Nickel 440                                                         | 8/26/70 | 14            | 20,000     | 15.5 (.0587)                                    | --                                    | --                                                        | 171 (95)                      | 183 (102)                | 190 (106)                  | 179 (99)  | Same remarks as test 9, except initial loads were 970 lb (3870 N) and 1060 lb (4715 N).                                                                                                                                                                                                                                                                                                                                                     |
| 11       | HyMu 80                                                                    | 9/1/70  | 4             | 20,000     | 15.3 (.0579)                                    | --                                    | --                                                        | --                            | 179 (99)                 | 190 (106)                  | 176 (98)  | Same remarks as test 9, except initial loads were 930 lb (3692 N) and 1030 lb (4581 N). Discovered that shaft assembly axial movement resulting from bearing wear was allowing the load piston to bottom out in housing bore. This resulted in complete loss of load on the upstream bearing and a load reduction to approximately 200 lb (889 N) on the downstream bearing. Resulting shaft gyrations caused labyrinth seal to shaft rubs. |
| 12       | Inco 600 with impregnate of LiF                                            | 9/3/70  | 60            | 20,000     | 15.8 (.0598)                                    | 830 (3692)                            | 1010 (4492)                                               | 179 (99)                      | 179 (99)                 | 183 (102)                  | 181 (101) | Reworked load piston to prevent bottoming prior to test 12. No excessive vibration or shaft rub was experienced.                                                                                                                                                                                                                                                                                                                            |
| 13       | Berylco Nickel 440 coated with a fused mixture of LiF and CaF <sub>2</sub> | 9/8/70  | 60            | 20,000     | 16.7 (.0632)                                    | 795 (3536)                            | 1095 (4870)                                               | 174 (97)                      | 174 (97)                 | 185 (103)                  | 180 (100) | No problems experienced during test.                                                                                                                                                                                                                                                                                                                                                                                                        |



TABLE VII (Cont.)

| Test No. | Separator Material                                           | Date               | Duration, min | Speed, RPM | Axial Load                            |                                                           | Temperatures                  |                          |                            |                              | Remarks                                                                                                                                                                                                                                                                                                                                |
|----------|--------------------------------------------------------------|--------------------|---------------|------------|---------------------------------------|-----------------------------------------------------------|-------------------------------|--------------------------|----------------------------|------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|          |                                                              |                    |               |            | Upstream Bearing, lb <sub>f</sub> (N) | Downstream Bearing, lb <sub>f</sub> (m <sup>3</sup> /min) | LF <sub>2</sub> Inlet, or (K) | Upstream Bearing, or (K) | Downstream Bearing, or (K) | LF <sub>2</sub> Exit, or (K) |                                                                                                                                                                                                                                                                                                                                        |
| 14       | Inco 600 with impregnate of LiF and CaF <sub>2</sub> mixture | 9/9/70             | 3             | 20,000     | 870 (3870)                            | 1050 (3670)                                               | 174 (97)                      | 178 (99)                 | 188 (104)                  | 179 (99)                     | Premature shutdown due to speed losses with constant pressure to the drive turbine. Just prior to shutdown the speed loss was approximately 1250 RPM. The speed losses were accompanied by slight temperature increases of the upstream bearing. Bearing was intact upon disassembly.                                                  |
| 15       | Rene' 41                                                     | 9/11/70            | 60            | 20,000     | 830 (3692)                            | 1060 (4715)                                               | 179 (99)                      | 179 (99)                 | 179 (99)                   | 179 (99)                     | No problems occurred during test.                                                                                                                                                                                                                                                                                                      |
| 16       | HyMu 80                                                      | 9/15/70            | 1             | 20,000     | --                                    | --                                                        | --                            | --                       | --                         | --                           | Premature shutdown due to appearance of a fire on the test stand. No fire existed. Scheduled test 17 with same hardware.                                                                                                                                                                                                               |
| 17       | Same test bearings as 016                                    | 9/16/70            | 46            | 20,000     | 810 (3603)                            | 1030 (4581)                                               | 183 (102)                     | 183 (102)                | 183 (102)                  | 183 (102)                    | Premature shutdown due to shaft displacement readings in excess of the labyrinth seal clearance. However upon disassembly no indication of shaft-to-labyrinth rub was seen.                                                                                                                                                            |
| 18       | Bervlico Michel 440                                          | 9/17/70            | 60            | 20,000     | 815 (3623)                            | 1030 (4581)                                               | 181 (101)                     | 183 (102)                | 190 (106)                  | 183 (102)                    | No problems were experienced during this test.                                                                                                                                                                                                                                                                                         |
| 19       | Inco 600 with impregnate of LiF and CaF <sub>2</sub> mixture | 9/18/70            | 7             | 20,000     | 860 (3823)                            | 1050 (4670)                                               | 175 (97)                      | 177 (98)                 | 172 (96)                   | 179 (99)                     | Premature shutdown due to speed losses with constant pressure to the drive turbine. Just prior to shutdown the speed loss was approximately 1200 RPM. The speed losses were accompanied by slight temperature increases of the upstream bearing. Bearing was intact upon disassembly. This was a repeat of test 14 with this material. |
| 20<br>21 | Bervlico Michel 440                                          | 6/25/71<br>6/29/71 | 60            | 20,000     | 770 (3425)                            | 980 (4359)                                                | 183 (102)                     | 183 (102)                | 183 (102)                  | 183 (102)                    | No problems were experienced during these tests. The one-hour duration was made in two runs with two days between runs. The bearings had ball unloading chutes ground in their inner raceways.                                                                                                                                         |

TABLE VII (Cont.)

| Test No. | Separator Material              | Date   | Duration, min | Speed, RPM | Axial Load                            |                                             | Temperatures                                    |                                        |                          |                                       | Remarks                                                                                                                                                                                                                                                                                       |
|----------|---------------------------------|--------|---------------|------------|---------------------------------------|---------------------------------------------|-------------------------------------------------|----------------------------------------|--------------------------|---------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|          |                                 |        |               |            | Upstream Bearing, lb <sub>f</sub> (N) | Downstream Bearing, lb <sub>f</sub> (m/min) | LP <sub>2</sub> Flow, gpm (m <sup>3</sup> /min) | LP <sub>2</sub> Inlet, Bearing, °R (K) | Upstream Bearing, °R (K) | LP <sub>2</sub> Exit, Bearing, °R (K) |                                                                                                                                                                                                                                                                                               |
| 22       | Inco 600 with impregnate of LiF | 7/1/71 | 35            | 20,000     | 760 (3380)                            | 990 (4404)                                  | 16.6 (.0628)                                    | 189 (105)                              | 190 (106)                | 190 (106)                             | Premature shutdown due to a sudden speed loss of 2000 RPM with a corresponding temperature increase of the upstream bearing. Upon disassembly it was discovered that the ball separator in this bearing had fractured. The bearings had ball unloading chutes ground in their inner raceways. |
| 23       | Berylico Nickel 440             | 7/2/71 | 60            | 20,000     | 830 (3692)                            | 1040 (4626)                                 | 16.6 (.0628)                                    | 192 (107)                              | 192 (107)                | 192 (107)                             | No problems were experienced during this test. The bearings had ball unloading chutes.                                                                                                                                                                                                        |
| 24       | Berylico Nickel 440             | 7/6/71 | 60            | 20,000     | 770 (3425)                            | 990 (4404)                                  | 16.5 (.0624)                                    | 196 (109)                              | 196 (109)                | 196 (109)                             | Same remarks as for test 23.                                                                                                                                                                                                                                                                  |
| 25       | Inco 600 with impregnate of LiF | 7/7/71 | 55            | 20,000     | 780 (3469)                            | 995 (4426)                                  | 16.5 (.0624)                                    | 187 (104)                              | 187 (104)                | 187 (104)                             | Premature shutdown due to a sudden speed loss of 2000 RPM with a corresponding temperature rise of the downstream bearing. Upon disassembly it was discovered that the ball separator in this bearing had fractured. The bearings had ball unloading chutes.                                  |
| 26       | Inco 600 with impregnate of LiF | 7/8/71 | 60            | 20,000     | 770 (3425)                            | 990 (4404)                                  | 16.5 (.0624)                                    | 192 (107)                              | 192 (107)                | 192 (107)                             | No problems were experienced during this test. The bearings had ball unloading chutes.                                                                                                                                                                                                        |

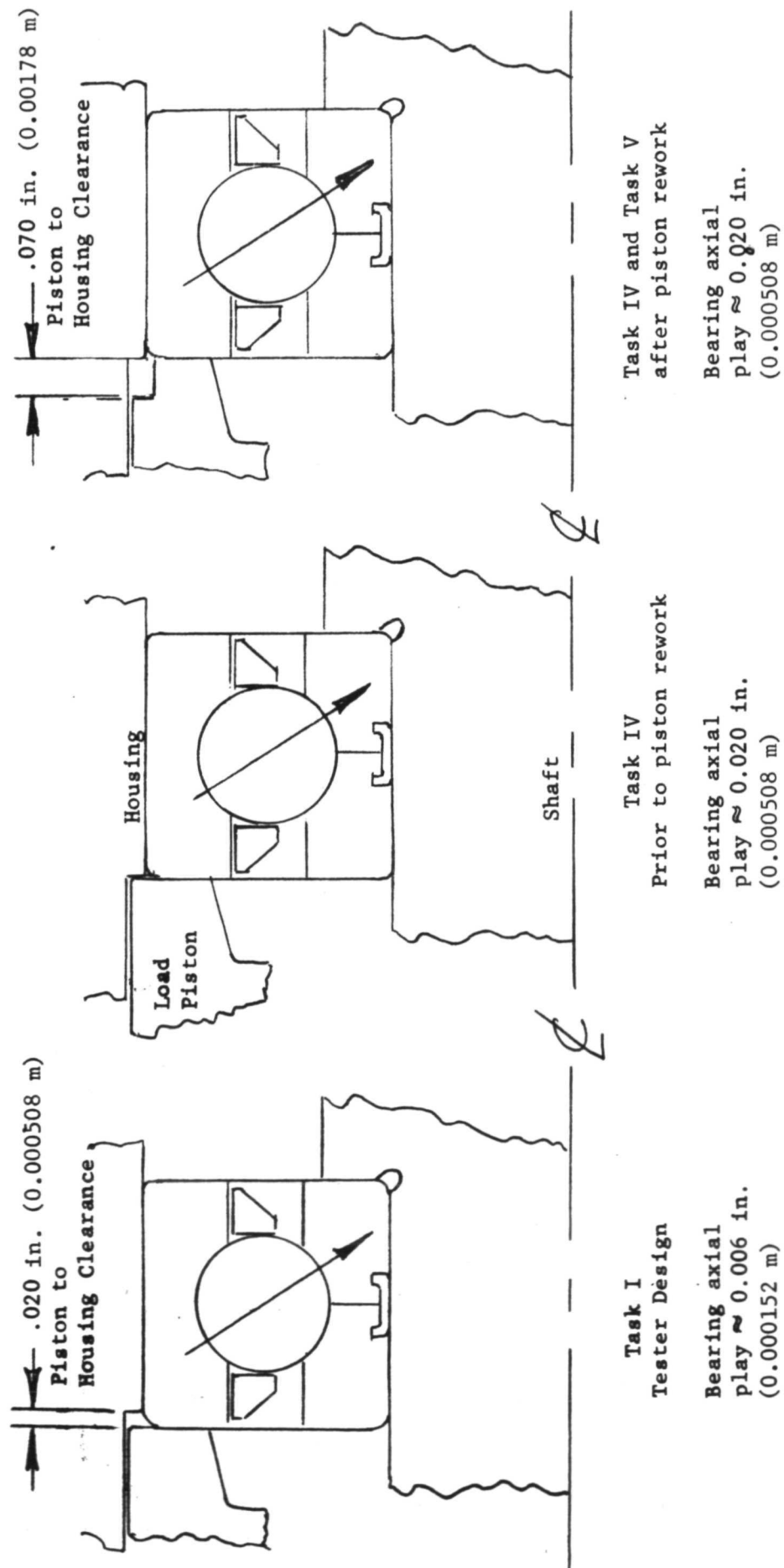


Figure 12. Tester Load Piston Design Modification

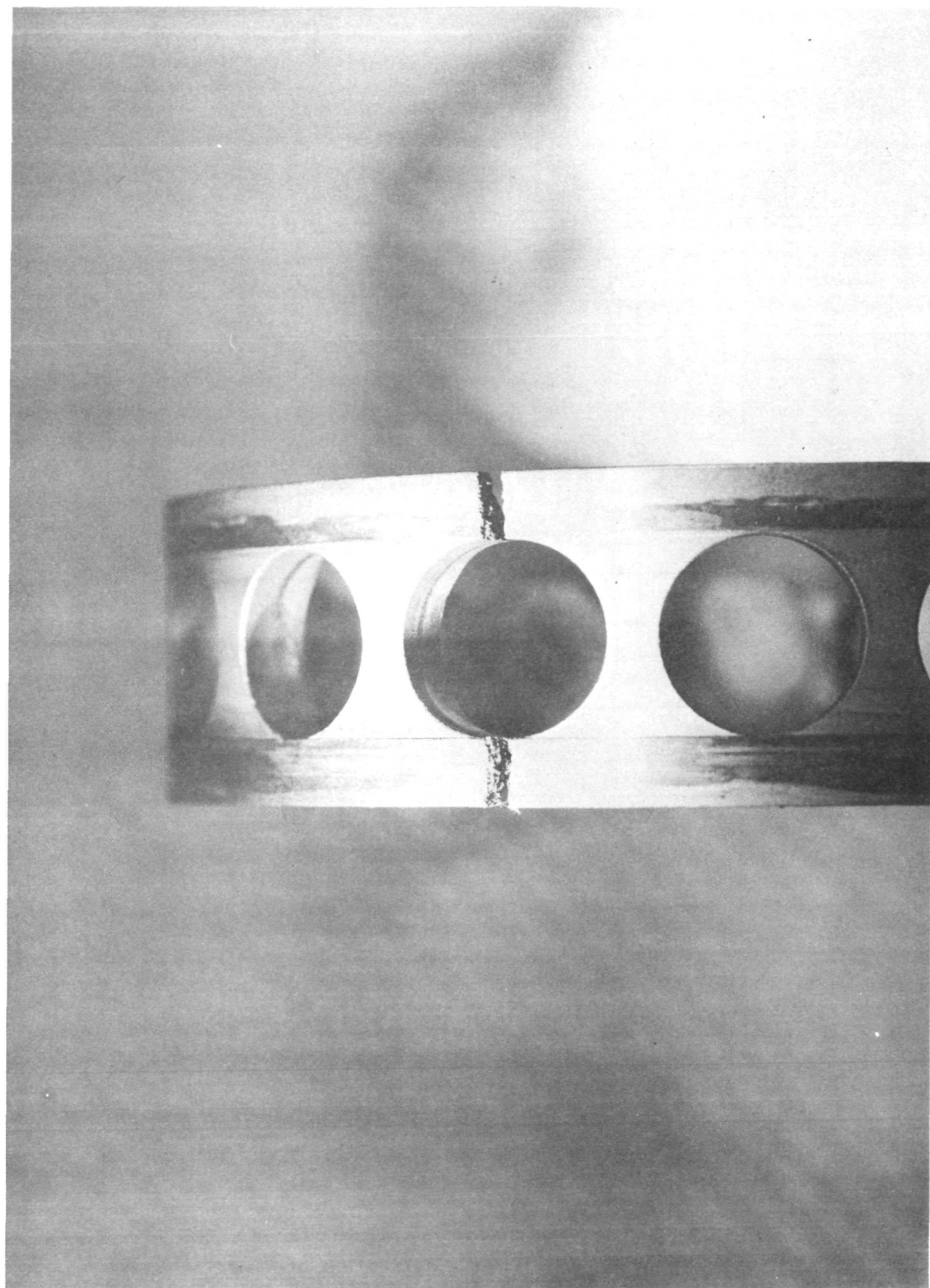


Figure 13. Ball Separator Fracture

## VII. ONE-HOUR BEARING EVALUATION TESTS IN FLOX - TASK V

The initial test plan for this task was programmed as a duplicate of Task IV except that FLOX in place of liquid fluorine was the test fluid. A total of eighteen one-hour tests were scheduled on three specimens each of six separator materials. During Task IV, several tester related problems and the design of a bearing modification to minimize wear resulted in unplanned expenses and, consequently, a reduction in scope.

Under the reduced scope program two materials, LiF impregnated INCO 600 and Berylco Nickel 440 were evaluated in three tests at 20,000 rpm and 800 pounds (3590N) load. The bearings used in this task were as originally designed and did not include the unloading chute. The first test, using the INCO 600 LiF impregnated cage, was aborted after 10 minutes of run time because of a decrease in tester speed coupled with a measured increase in bearing temperature. The observed speed change and temperature rise were similar to that previously experienced with fractured cages, however, post test inspection of the bearing did not reveal the cause of the temperature rise or speed decrease. Because this cage material had fractured on two previous liquid fluorine tests and because of the reduced scope, emphasis was shifted to testing the solid material separators. Two one-hour tests were performed without difficulty using separators of Berylco Nickel 440.

Steady state data from all three tests are tabulated in Table VIII. Post test measurements are presented in Section VIII, together with a discussion of test results.

TABLE VIII

## TASK V ONE-HOUR DURATION TESTS IN FLOX STEADY-STATE DATA

| Test No. | Separator Material              | Date    | Duration, min | Speed, RPM | LF <sub>2</sub> Flow, gpm<br>(m <sup>3</sup> /min) | Axial Load                               |                                                              | Temperatures                     |                             |                               |                                 | Remarks                                                                                                                                                              |
|----------|---------------------------------|---------|---------------|------------|----------------------------------------------------|------------------------------------------|--------------------------------------------------------------|----------------------------------|-----------------------------|-------------------------------|---------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|          |                                 |         |               |            |                                                    | Upstream Bearing, lb <sub>f</sub><br>(N) | Downstream Bearing, lb <sub>f</sub><br>(m <sup>3</sup> /min) | LF <sub>2</sub> Inlet, °R<br>(K) | Upstream Bearing, °R<br>(K) | Downstream Bearing, °R<br>(K) | LF <sub>2</sub> Exit, °R<br>(K) |                                                                                                                                                                      |
| 1        | Inco 600 with impregnate of LiF | 7/28/71 | 10            | 20,000     | 16.4<br>(.0621)                                    | 730<br>(3247)                            | 960<br>(4270)                                                | 179<br>(99)                      | 179<br>(99)                 | 179<br>(99)                   | 179<br>(99)                     | Premature shutdown due to speed loss of approximately 1250 RPM with a corresponding temperature rise of the upstream bearing. No problem was noted upon disassembly. |
| 2        | Berylico Mickel 440             | 7/29/71 | 60            | 20,000     | 16.4<br>(.0621)                                    | 770<br>(3425)                            | 1000<br>(4448)                                               | 183<br>(102)                     | 183<br>(102)                | 183<br>(102)                  | 183<br>(102)                    | No problems were noted during this test.                                                                                                                             |
| 3        | Berylico Mickel 440             | 7/29/71 | 60            | 20,000     | 16.6<br>(.0628)                                    | 760<br>(3380)                            | 960<br>(4270)                                                | 187<br>(104)                     | 187<br>(104)                | 187<br>(104)                  | 187<br>(104)                    | No problems were noted during this test.                                                                                                                             |

## VIII. TEST DATA ANALYSIS

### A. MATERIAL EVALUATION TESTS

The intent of the Task I material evaluation tests was to establish the relative order of the three cage-materials (Berylco Nickel 440, HyMu 80, Rene' 41) in providing effective fluoride lubrication. No definitive pattern in component wear was established, consequently no conclusion could be drawn as to which cage material was best. A comparison of the cage ball pocket wear scar minor axis measurements is given in Figures 14, 15 and 16 for the 400 lb (1779N), 800 lb (3558N), and 1200 lb (5338N) load series tests, respectively. A comparison of the measured ball wear is given in Figures 17, 18, and 19 for the three load series. The cage and ball wear were comparable at 7000 and 14,000 rpm but quite irregular at 20,000 rpm. Wear increased rapidly as speed increased. As expected, cage wear was not affected by axial load and the ball wear tended to increase with load.

Inner race wear measurements are tabulated in Table IX. The three bearings with Rene' 41 cages which were located in the downstream tester position show a trend of increasing inner race wear with load and this data is plotted in Figure 20. However, the other inner race wear data shown on the table show no such trend. In all cases the maximum wear depth was located at a contact angle of approximately 40°.

An emission spectroscopy analysis of the deposits found on the loaded inner races of several bearings from Task I showed only a minor amount (less than 10%) of nickel present. The major metal constituent of the deposits was definitely identified as iron. Both electron diffraction and X-ray diffraction techniques were used to further identify the compounds as  $\text{FeF}_2$  and  $\text{Fe}_2\text{F}_{5.7}\text{H}_2\text{O}$  with traces of  $\text{Fe}_3\text{O}_4$ . The hydrate and iron oxide were undoubtedly formed during the exposures to atmospheric conditions between the tests and the analysis. Because of the similarity in defraction patterns of iron and nickel fluorides and the large percentage of iron present, the exact nickel form could not be identified.

An electron diffraction is shown on Figure 21 along with a 100,000 magnification of the raceway. The measured radii of the rings in Angstroms (Å) identify the compound by comparison with standard models. The X-ray diffraction analysis was in complete agreement with the electron diffraction analysis. A comparison of the measured radii and the standard Angstrom models of  $\text{FeF}_2$  and  $\text{Fe}_2\text{F}_{5.7}\text{H}_2\text{O}$  is presented as Table X. Note that the major constituents were identified to be either of these two compounds. A "melt" was performed during the electron diffraction analysis. This consisted of driving off the 7  $\text{H}_2\text{O}$  molecules from the hydrate by increasing the power input of the high-intensity electron beam. Then, only  $\text{FeF}_2$  crystals were left.

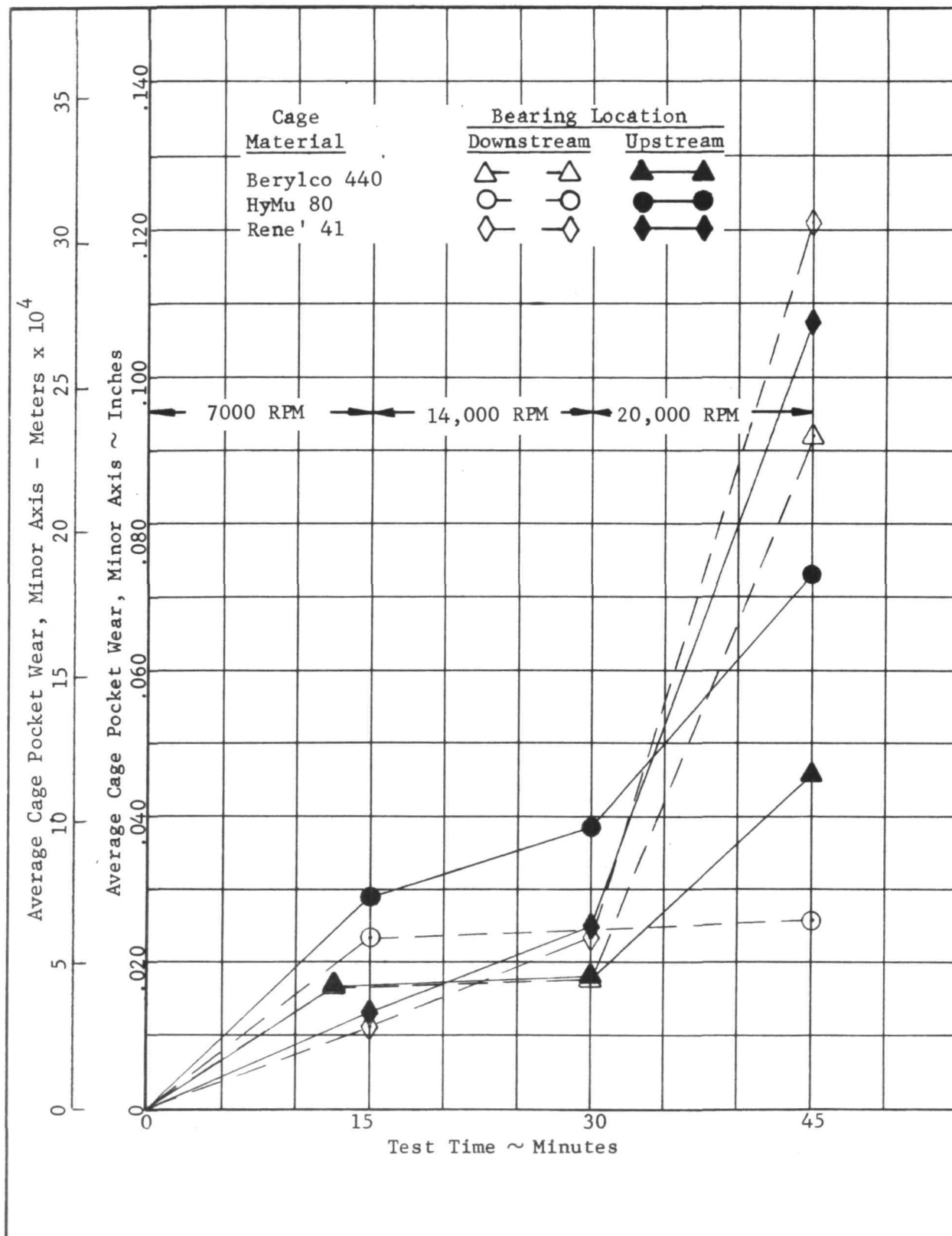


Figure 14. Separator Wear with 400-lb (1790 N) Load  
Task I Testing in  $LF_2$



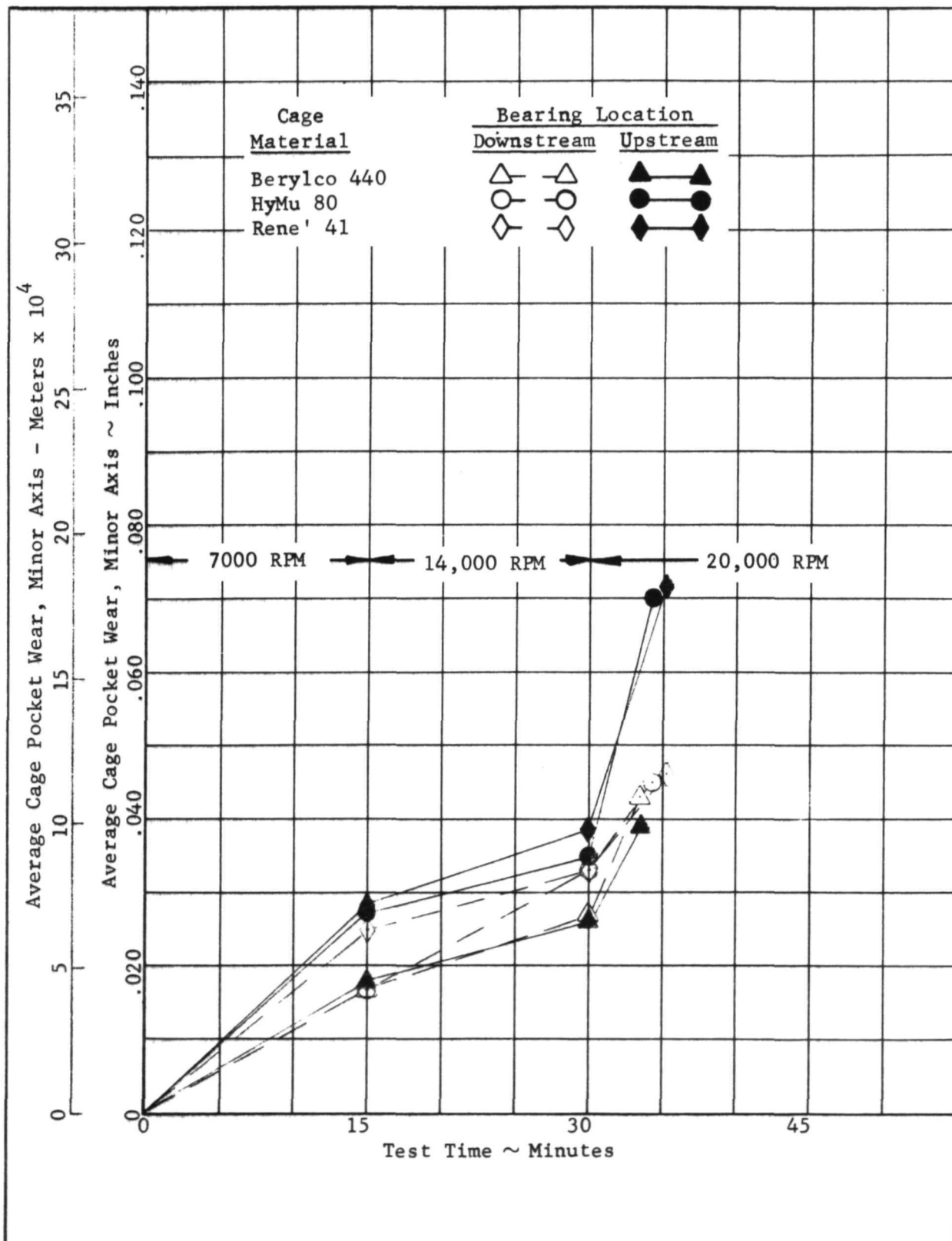


Figure 15. Separator Wear with 800-lb (3590 N) Load  
Task I Testing in  $LF_2$

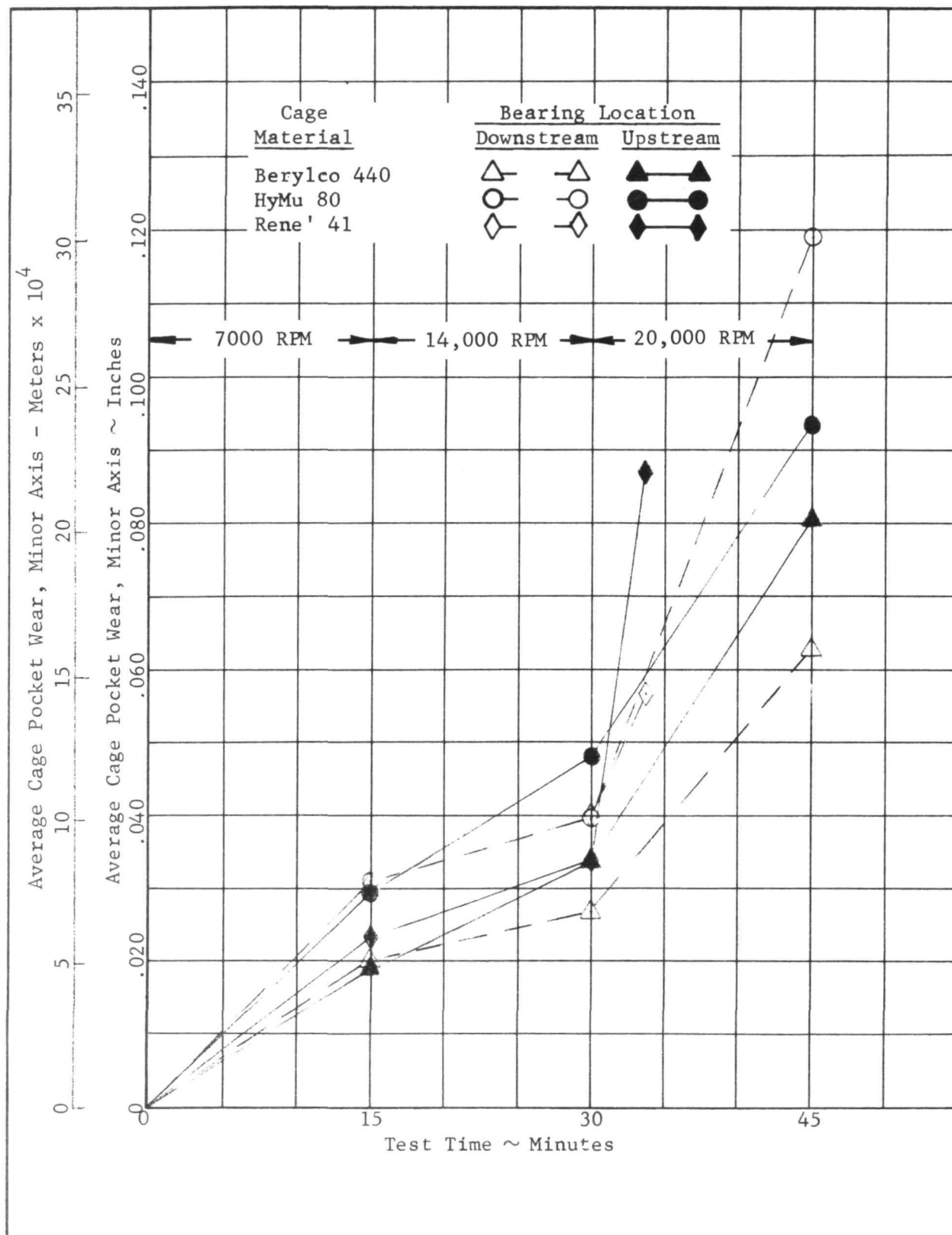


Figure 16. Separator Wear with 1200-lb (5380 N) Load - Task I Testing in  $LF_2$

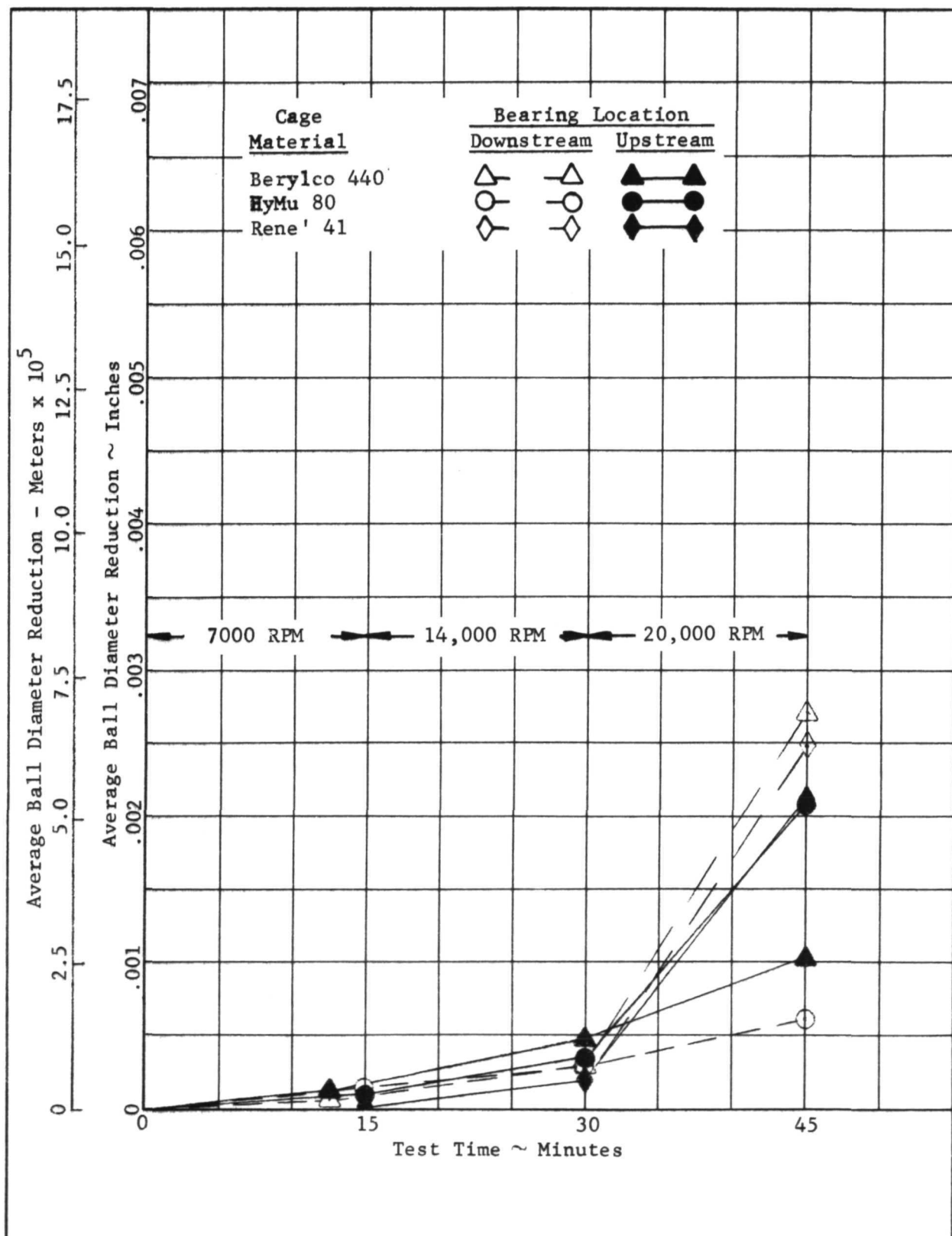


Figure 17. Ball Wear with 400-lb (1790 N) Load - Task I Testing in LF<sub>2</sub>

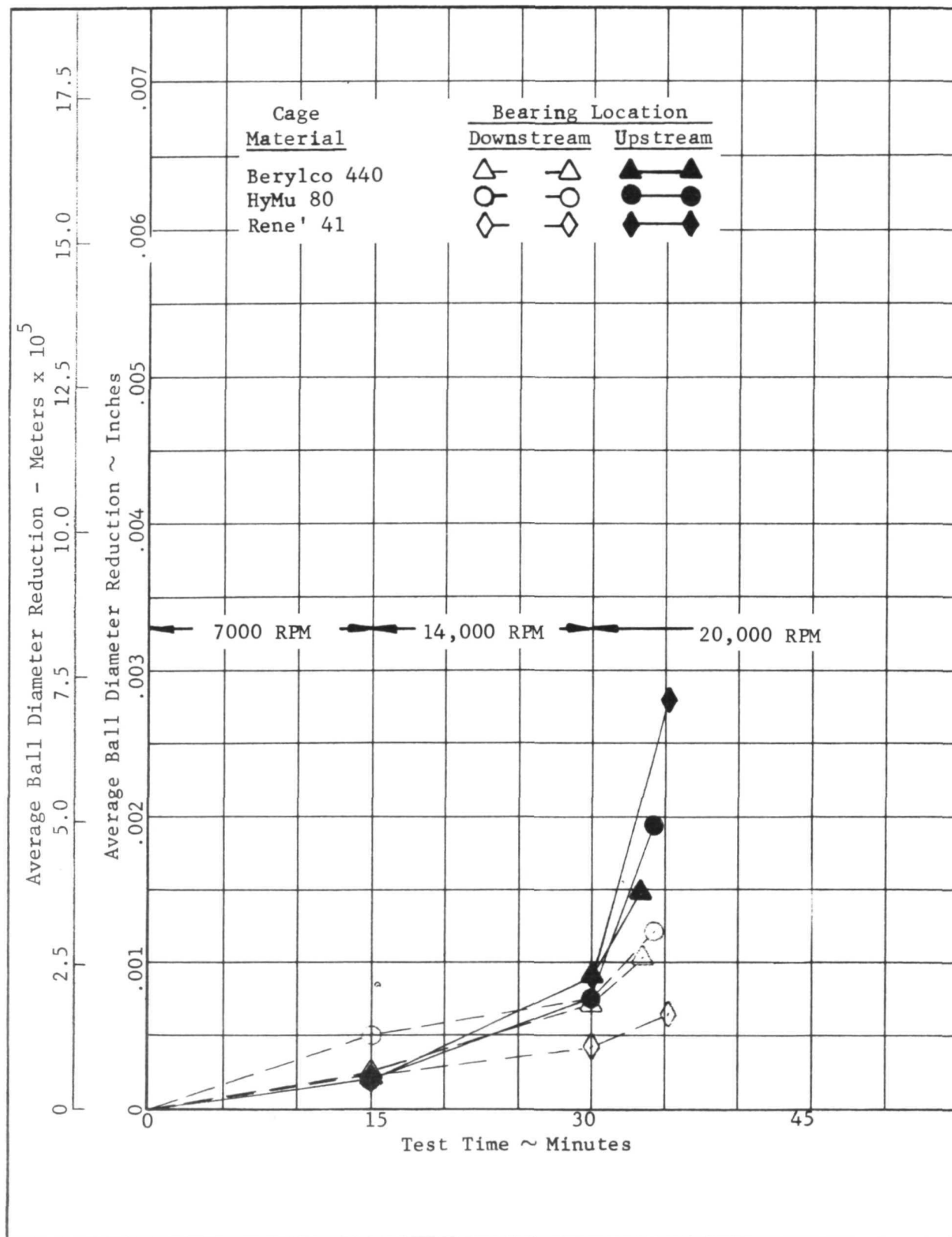


Figure 18. Ball Wear with 800-lb (3590 N) Load - Task I Testing in  $LF_2$

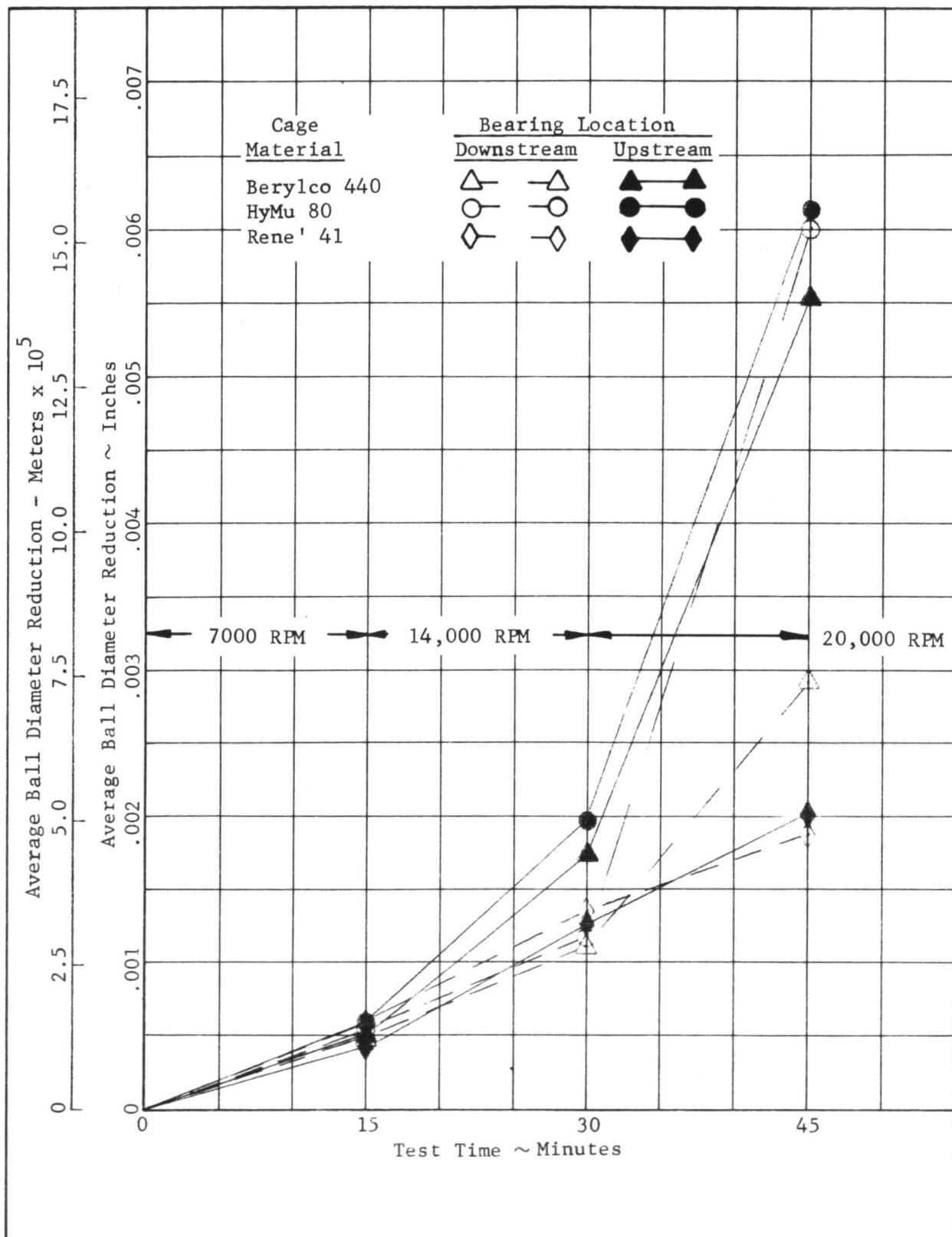


Figure 19. Ball Wear with 1200-lb (5380 N) - Load - Task I Testing in  $LF_2$

TABLE IX

## TASK I - INNER RACE WEAR IN LIQUID FLUORINE

| Material    | UPSTREAM BEARING |                           |                       | DOWNSTREAM BEARING |                           |                       | Total<br>Test Time,<br>min | Test Load |      |
|-------------|------------------|---------------------------|-----------------------|--------------------|---------------------------|-----------------------|----------------------------|-----------|------|
|             | Inner Race Wear  |                           |                       | Inner Race Wear    |                           |                       |                            | lb        | N    |
|             | inch             | meters x 10 <sup>-4</sup> | Contact Angle,<br>deg | inch               | meters x 10 <sup>-4</sup> | Contact Angle,<br>deg |                            |           |      |
| Berylco 440 | .0006            | .152                      | 40                    | .00106             | .269                      | 42                    | 10,13,16                   | 400       | 1780 |
|             | .0006            | .152                      | 41                    | .00058             | .147                      | 42                    | 20,23,26                   | 800       | 3560 |
|             | .00083           | .211                      | 45                    | .0008              | .203                      | 43                    | 35,38,41                   | 1200      | 5340 |
| HyMu 80     | .00067           | .170                      | 43                    | .00062             | .157                      | 40                    | 11,14,17                   | 400       | 1780 |
|             | .0007            | .178                      | 37                    | .0005              | .127                      | 40                    | 19,22,25                   | 800       | 3560 |
|             | .00085           | .216                      | 37                    | .00057             | .145                      | 42                    | 34,37,40                   | 1200      | 3340 |
| Rene' 41    | .00082           | .208                      | 43                    | .00045             | .114                      | 40                    | 12,15,18                   | 400       | 1780 |
|             | .00052           | .132                      | 38                    | .00065             | .165                      | 41                    | 21,24,27                   | 800       | 3560 |
|             | .00083           | .211                      | 45                    | .0007              | .178                      | 45                    | 35,39,42                   | 1200      | 5340 |
| Berylco 440 | .00057           | .145                      | 45                    | .0093              | .236                      | 42                    | 31                         | Variable  |      |
|             | --               | --                        | --                    | .00047             | .119                      | 45                    | 32/33                      | Variable  |      |

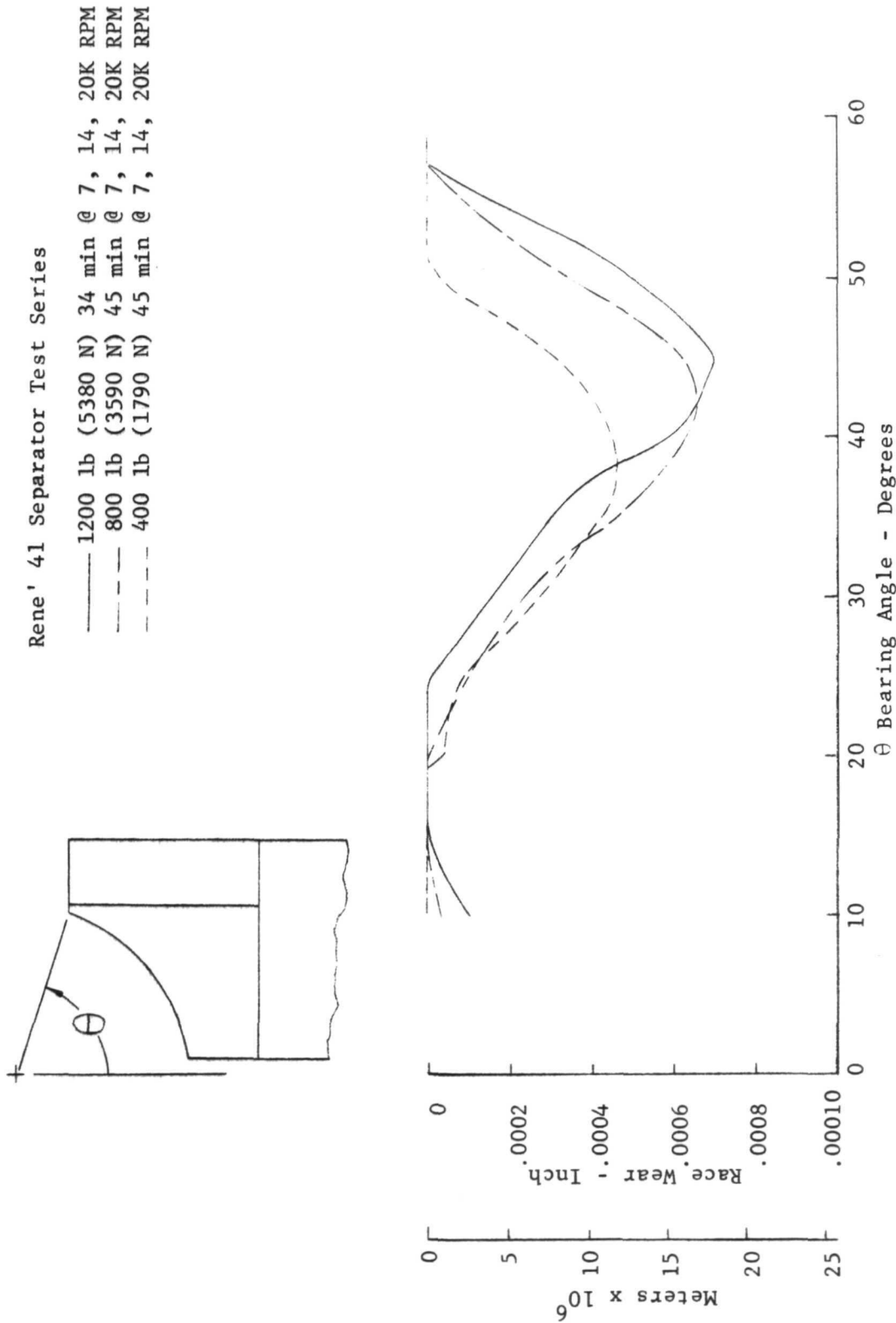


Figure 20. Comparison of Inner Race Wear for Bearings Run at 400, 800, and 1200-lb (1790, 3590, 5380 N) During Task I

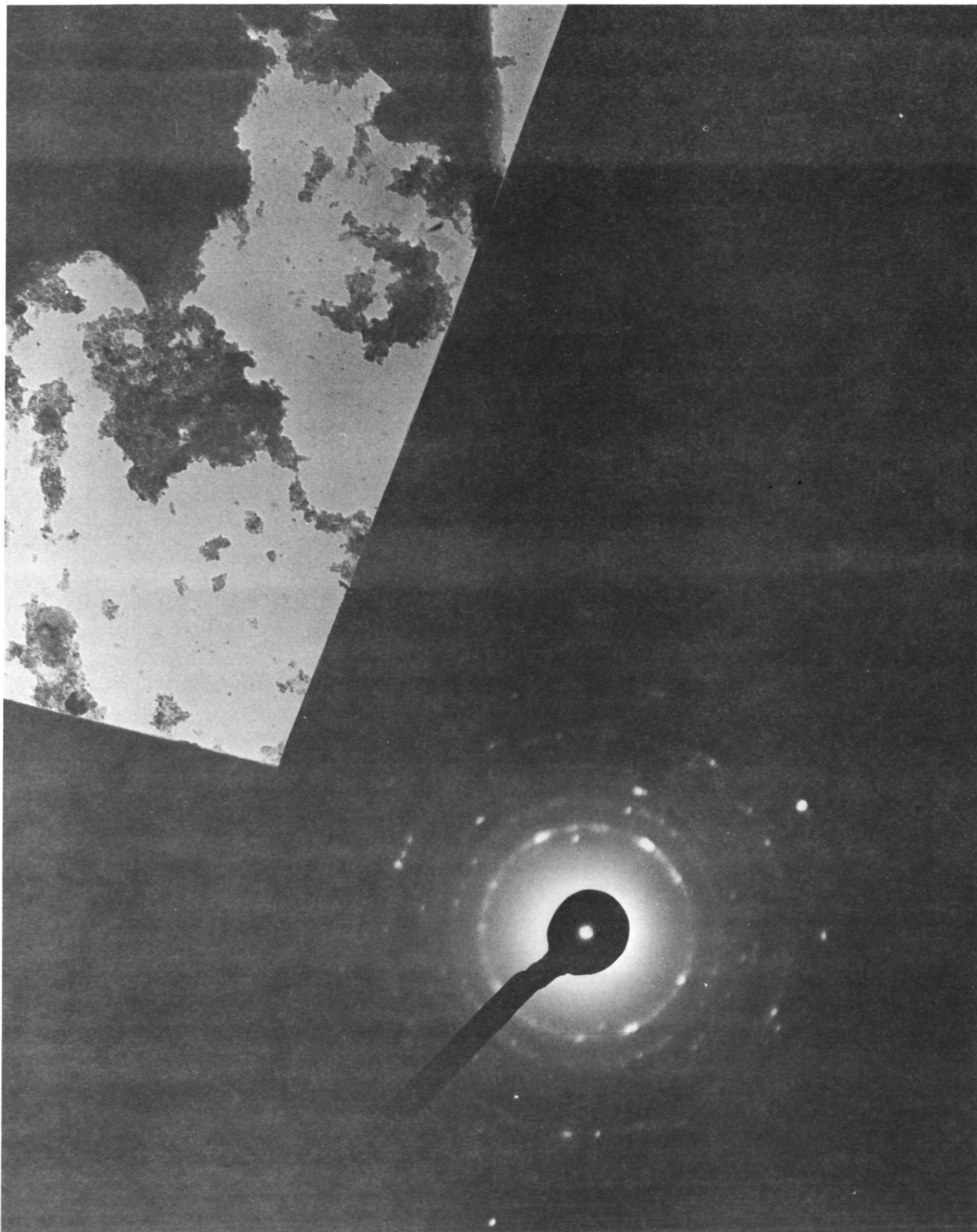


Figure 21. Electron Diffraction of Iron-Fluoride Crystal



TABLE X

## COMPARISON OF CRYSTAL DEPOSITS

| Standard<br>Model<br>(Å) | Electron Defraction Data                                |                       |
|--------------------------|---------------------------------------------------------|-----------------------|
|                          | $\text{Fe}_2\text{F}_5\cdot 7\text{H}_2\text{O}$<br>(Å) | $\text{FeF}_2$<br>(Å) |
| 4.885                    | -                                                       | 4.86                  |
| 4.773                    | 4.69                                                    | -                     |
| 4.585                    | 4.51                                                    | 4.60                  |
| 4.319                    | 4.25                                                    | 4.31                  |
| 3.832                    | 3.81                                                    | 3.85                  |
| 3.710                    | -                                                       | -                     |
| 3.513                    | 3.48                                                    | -                     |
| 3.326                    | -                                                       | -                     |
| 3.245                    | 3.22                                                    | 3.25                  |
| 3.025                    | -                                                       | -                     |
| 2.864                    | -                                                       | -                     |
| 2.789                    | 2.74                                                    | -                     |
| 2.609                    | 2.60                                                    | 2.65                  |
| 2.507                    | 2.50                                                    | -                     |
| 2.419                    | 2.41                                                    | -                     |
| 2.144                    | 2.14                                                    | -                     |
| 2.063                    | 2.05                                                    | -                     |
| 1.921                    | 1.92                                                    | 1.92                  |
| 1.889                    | 1.88                                                    | 1.90                  |
| 1.831                    | 1.82                                                    | 1.83                  |
| 1.755                    | -                                                       | 1.78                  |
| 1.683                    | -                                                       | 1.67                  |
| 1.662                    | -                                                       | 1.67                  |

## VIII, Test Data Analysis (cont.)

### B. ONE-HOUR BEARING EVALUATION TESTS IN LIQUID FLUORINE

The incorporation of a ball unloading chute in the inner raceway did not reduce ball wear. Post test cage ball pocket minor axis and ball diameter reduction measurements are tabulated for all Task IV tests in Table XI. Post test inner race wear measurements are tabulated in Table XII. A circle around the test number indicates that the bearings in that test had ball unloading chutes. A triangle around the test number indicates that axial loading was lost completely on the upstream bearing and reduced to approximately 200 lb (890N) on the downstream bearing sometime during the test.

A comparative plot of the cage and ball wear as a function of cage material is shown in Figure 22. This plot includes the data from tests 17 and 25 which were terminated at 47 min and 55 min, respectively, but excludes all data from the shorter duration tests. Therefore, all tests in which cages of INCO 600, impregnated with Li/CaF<sub>2</sub>, were used also are excluded. As can be seen, the data is inconsistent; however, it could be concluded that the ball wear was less when using cages of sintered INCO 600 infiltrated with lithium fluoride. The wear of the INCO 600 cages, regardless of impregnant, was definitely greater than any of the solid material separators. When using bearings with ball unloading chutes, two out of six (tests 22 and 25) LiF infiltrated INCO 600 cages fractured axially across one ball pocket. A photo of the cage from test 22 is shown in Figure 13. All of the tests conducted with bearings incorporating sintered INCO 600 infiltrated with a mixture of calcium fluoride-lithium fluoride were terminated because of indicated bearing problems, erratic torque, and temporary outer race temperature rises. As can be seen from Table XI, the cage wear experienced with this material was large even for the very short durations.

Inner race wear was independent of the cage material. Outer race wear measurements were not recorded primarily because of inspection equipment problems. However, the absence of a ball wear track, compared to the visual appearance of the inner race, indicated that outer race wear was negligible. For equivalent load, speed, and duration, the inner race wear depth was nearly the same regardless of cage material. The maximum wear depth measured was near the inner ring land in all cases. The downstream bearing in test 13 was near failure. The balls had worn 0.010 inch ( $2.54 \times 10^{-4}$  m) and the race wear depth of 0.0065 in. ( $1.65 \times 10^{-4}$  m) was measured at the raceway edge. Figure 23 is a plot of measured inner race wear versus contact angle for this bearing.

### C. ONE-HOUR BEARING EVALUATION TESTS IN FLOX

Bearing ball and race wear were considerably less in 83.6% FLOX than in liquid fluorine. Ball and cage wear measurements are tabulated in Table XIII. Inner race wear measurements are tabulated in Table XIV. In two

TABLE XI

TASK IV BALL AND SEPARATOR POCKET WEAR  
IN LIQUID FLUORINE

| Material                                     | Test No. | UPSTREAM BEARING |                                             |                                             | DOWNSTREAM BEARING |                                             |                                             | CASE - MINOR AXIS |                          |            |                          | Total<br>Test Time |
|----------------------------------------------|----------|------------------|---------------------------------------------|---------------------------------------------|--------------------|---------------------------------------------|---------------------------------------------|-------------------|--------------------------|------------|--------------------------|--------------------|
|                                              |          | Ball             |                                             |                                             | Ball               |                                             |                                             | Upstream          |                          | Downstream |                          |                    |
|                                              |          | in               | Dia. Reduction,<br>meters x 10 <sup>4</sup> | Dia. Reduction,<br>meters x 10 <sup>4</sup> | in                 | Dia. Reduction,<br>meters x 10 <sup>4</sup> | Dia. Reduction,<br>meters x 10 <sup>4</sup> | in                | meters x 10 <sup>4</sup> | in         | meters x 10 <sup>4</sup> |                    |
| HyMu 80                                      | 1        | .0031            | .787                                        | .0091                                       | .0091              | 2.311                                       | .06141                                      | 15.60             | .07992                   | 20.30      | 60                       |                    |
|                                              | 11       | .0007            | .178                                        | .002                                        | .002               | .508                                        | .05039                                      | 12.80             | .06811                   | 17.30      | 4                        |                    |
|                                              | 16-17    | .0095            | 2.413                                       | .008                                        | .008               | 2.032                                       | .06457                                      | 16.40             | .08464                   | 21.50      | 47                       |                    |
| Berylico Nickel 440<br>Coated                | 2        | .004             | 1.016                                       | .008                                        | .008               | 2.032                                       | .05984                                      | 15.20             | .09390                   | 23.85      | 60                       |                    |
|                                              | 13       | .0055            | 1.397                                       | .010                                        | .010               | 2.540                                       | .08507                                      | 21.61             | .04465                   | 11.34      | 60                       |                    |
| Berylico Nickel 440                          | 3        | .005             | 1.270                                       | .0075                                       | .0075              | 1.905                                       | .05551                                      | 14.10             | .08268                   | 21.00      | 60                       |                    |
|                                              | 10       | .0007            | .178                                        | .001                                        | .001               | .254                                        | .05417                                      | 13.76             | .03429                   | 8.71       | 14                       |                    |
|                                              | 18       | .010             | 2.540                                       | .004                                        | .004               | 1.016                                       | .08307                                      | 21.10             | .03929                   | 9.98       | 60                       |                    |
|                                              | 20       | .0047            | 1.194                                       | .0057                                       | .0057              | 1.448                                       | .06630                                      | 16.84             | .06252                   | 15.88      | 60                       |                    |
|                                              | 21       | .0073            | 1.854                                       | .0074                                       | .0074              | 1.880                                       | .09106                                      | 23.13             | .08161                   | 20.73      | 60                       |                    |
|                                              | 22       | .0082            | 2.083                                       | .0057                                       | .0057              | 1.448                                       | .07646                                      | 19.42             | .07008                   | 17.80      | 60                       |                    |
|                                              | 4        | .005             | 1.270                                       | .0093                                       | .0093              | 2.362                                       | .05768                                      | 14.65             | .07992                   | 20.30      | 60                       |                    |
|                                              | 5        | .0015            | .381                                        | .0006                                       | .0006              | .152                                        | .05708                                      | 14.50             | .04843                   | 12.30      | 7                        |                    |
| Inco 600 Impregnated<br>LiF/CaF <sub>2</sub> | 15       | .0075            | 1.905                                       | .0055                                       | .0055              | 1.397                                       | .06358                                      | 16.15             | .07228                   | 18.36      | 60                       |                    |
|                                              | 5        | .0015            | .381                                        | .003                                        | .003               | .762                                        | .08622                                      | 21.90             | .10000                   | 25.40      | 30                       |                    |
|                                              | 14       | .0003            | .076                                        | .0003                                       | .0003              | .076                                        | .06142                                      | 15.60             | .07370                   | 18.72      | 3                        |                    |
|                                              | 19       | .0002            | .051                                        | .0003                                       | .0003              | .076                                        | .08130                                      | 20.65             | .07953                   | 20.20      | 7                        |                    |
| Inco 600 LiF                                 | 6        | .0027            | .686                                        | .0052                                       | .0052              | 1.321                                       | .10465                                      | 26.58             | .10626                   | 27.00      | 60                       |                    |
|                                              | 12       | .004             | 1.016                                       | .004                                        | .004               | 1.016                                       | Wear scar exceeds metal width               |                   |                          |            |                          | 60                 |
|                                              | 22       | .003             | .762                                        | .0025                                       | .0025              | .635                                        | .11968                                      | 30.40             | .12402                   | 31.50      | 35                       |                    |
|                                              | 23       | .0043            | 1.092                                       | .0041                                       | .0041              | 1.041                                       | .11925                                      | 30.29             | .12693                   | 32.24      | 55                       |                    |
|                                              | 24       | .0059            | 1.499                                       | .0054                                       | .0054              | 1.372                                       | .12492                                      | 31.73             | .13508                   | 34.31      | 60                       |                    |

○ Designates bearings had unloading chute.

△ Designates load was lost during test (piston bottomed).

TABLE XII

## TASK IV INNER RACE WEAR IN LIQUID FLUORINE

| Material                                       | UPSTREAM BEARING |                          |                    | DOWNSTREAM BEARING |                          |                    | Test No.        | Total Test Time min |
|------------------------------------------------|------------------|--------------------------|--------------------|--------------------|--------------------------|--------------------|-----------------|---------------------|
|                                                | Inner Race Wear  |                          | Contact Angle, deg | Inner Race Wear    |                          | Contact Angle, deg |                 |                     |
|                                                | inch             | meters x 10 <sup>4</sup> |                    | inch               | meters x 10 <sup>4</sup> |                    |                 |                     |
| Berylco 440                                    | .0002            | .051                     | 55                 | .0024              | .61                      | 55                 | △ <sub>3</sub>  | 60                  |
|                                                | .0008            | .203                     | 55                 | .0011              | .279                     | 55                 | △ <sub>10</sub> | 14                  |
|                                                | .0039            | .99                      | 55                 | .0031              | .787                     | 55                 | 18              | 60                  |
|                                                | .0035            | .89                      | 55                 | .004               | 1.02                     | 55                 | ⊙ <sub>21</sub> | 60                  |
|                                                | .039             | .99                      | 55                 | .004               | 1.02                     | 55                 | ⊙ <sub>23</sub> | 60                  |
|                                                | .004             | 1.02                     | 55                 | .004               | 1.02                     | 55                 | ⊙ <sub>24</sub> | 60                  |
| Berylco 440<br>CaF <sub>2</sub> -LiF<br>Coated | .001             | .254                     | 55                 | .0031              | .787                     | 55                 | △ <sub>2</sub>  | 60                  |
|                                                | .0029            | .737                     | 55                 | .0065              | 1.65                     | 55                 | 13              | 60                  |
|                                                | .0032            | .813                     | 55                 | .0013              | .330                     | 55                 | △ <sub>1</sub>  | 60                  |
| HyMu 80                                        | .001             | .254                     | 55                 | .0008              | .203                     | 55                 | △ <sub>11</sub> | 4                   |
|                                                | .004             | 1.02                     | 55                 | .0037              | .940                     | 55                 | 17              | 47                  |
|                                                | .001             | .254                     | 55                 | .0037              | .940                     | 55                 | △ <sub>4</sub>  | 60                  |
| Rene' 41                                       | .0011            | .279                     | 55                 | .0011              | .279                     | 55                 | △ <sub>9</sub>  | 7                   |
|                                                | .0038            | .965                     | 55                 | .0035              | .89                      | 55                 | 15              | 60                  |
|                                                | .0012            | .305                     | .50                | .0016              | .406                     | 55                 | △ <sub>5</sub>  | 30                  |
| Inco 600<br>CaF <sub>2</sub> -LiF              | .001             | .254                     | 55                 | .0005              | .127                     | 55                 | 14              | 3                   |
|                                                | .0014            | .356                     | 55                 | .0005              | .127                     | 55                 | 19              | 7                   |
|                                                | .0011            | .279                     | 55                 | .0033              | .838                     | 55                 | △ <sub>8</sub>  | 60                  |
| Inco 600<br>LiF                                | .0032            | .813                     | 55                 | .0036              | .914                     | 55                 | 12              | 60                  |
|                                                | .0016            | .406                     | 55                 | .0017              | .432                     | 55                 | ⊙ <sub>22</sub> | 35                  |
|                                                | .0031            | .787                     | 55                 | .0028              | .711                     | 55                 | ⊙ <sub>25</sub> | 55                  |
|                                                | .0038            | .965                     | 55                 | .0033              | .838                     | 55                 | ⊙ <sub>26</sub> | 60                  |
|                                                |                  |                          |                    |                    |                          |                    |                 |                     |
|                                                |                  |                          |                    |                    |                          |                    |                 |                     |

△ Designates load was lost during test (piston bottomed).

⊙ Designates bearings had unloading chute.

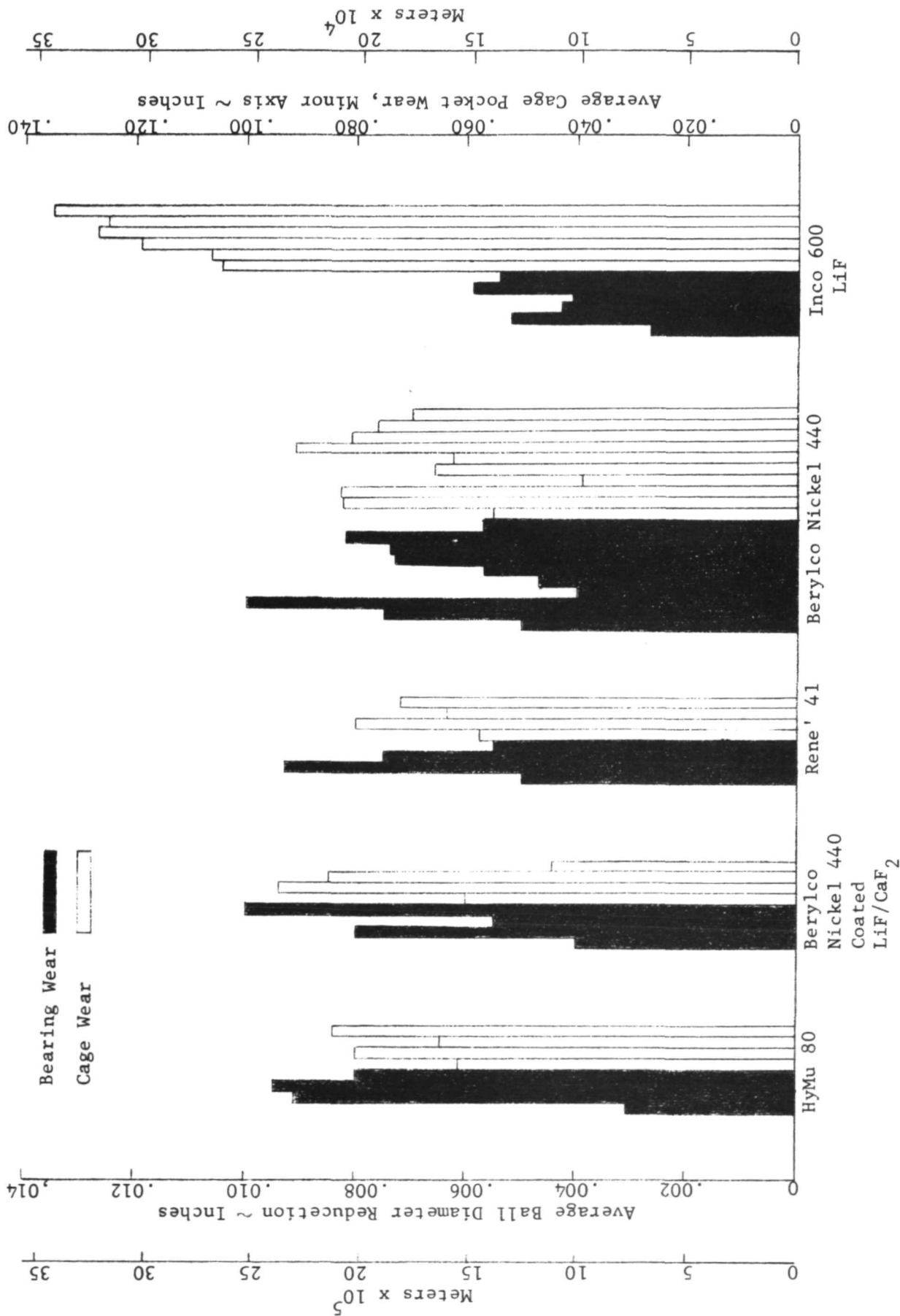


Figure 22. Comparison of Ball Wear and Separator Pocket Wear Scar for Task IV Tests

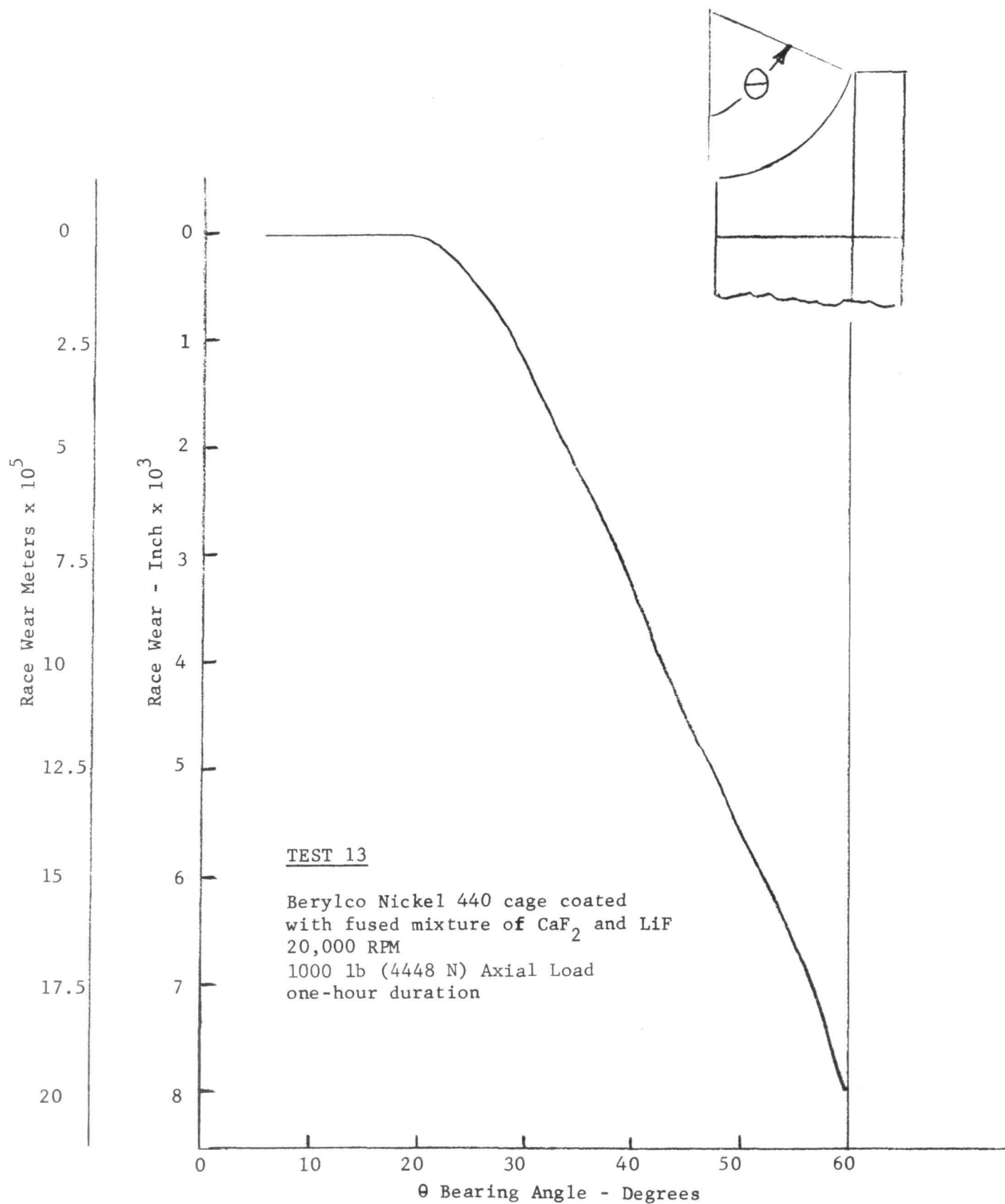


Figure 23. Inner Race Wear vs Contact Angle - Test 13

TABLE XIII  
TASK V BALL AND SEPARATOR POCKET WEAR IN FLOX

| <u>Material</u>           | <u>Test No.</u> | <u>Ball</u>                 |                               | <u>Cage Wear Seal</u> |                                           | <u>Total Test Time, minute</u> | <u>Position</u> |
|---------------------------|-----------------|-----------------------------|-------------------------------|-----------------------|-------------------------------------------|--------------------------------|-----------------|
|                           |                 | <u>Dia. Reduction, inch</u> | <u>meter x 10<sup>4</sup></u> | <u>inch</u>           | <u>Minor Axis, meter x 10<sup>4</sup></u> |                                |                 |
| Inco 600 LiF <sub>2</sub> | 001             | .0003                       | .076                          | .0888                 | 22.56                                     | 10                             | Upstream        |
| Inco 600 LiF <sub>2</sub> | 001             | .0003                       | .076                          | .0987                 | 25.07                                     | 10                             | Downstream      |
| Berylco 440               | 002             | .000725                     | .184                          | .0602                 | 15.27                                     | 60                             | Upstream        |
| Berylco 440               | 002             | .0006                       | .152                          | .0679                 | 17.24                                     | 60                             | Downstream      |
| Berylco 440               | 003             | .0019                       | .483                          | .0678                 | 17.22                                     | 60                             | Upstream        |
| Berylco 440               | 003             | .0008                       | .203                          | .0656                 | 16.66                                     | 60                             | Downstream      |

TABLE XIV  
TASK V INNER RACE WEAR IN FLOX

| Material     | UPSTREAM BEARING |                          |                    | DOWNSTREAM BEARING |                          |                    | Test Test Time, No. min |
|--------------|------------------|--------------------------|--------------------|--------------------|--------------------------|--------------------|-------------------------|
|              | Inner Race Wear  |                          | Contact Angle, deg | Inner Race Wear    |                          | Contact Angle, deg |                         |
|              | inch             | meters x 10 <sup>4</sup> |                    | inch               | meters x 10 <sup>4</sup> |                    |                         |
| Inco 600 Lip | .0008            | .203                     | 55                 | .0008              | .203                     | 55                 | 10                      |
|              |                  |                          |                    |                    |                          |                    |                         |
| Berylco 440  | .0012            | .305                     | 45                 | .0007              | .178                     | 42                 | 60                      |
|              | .002             | .508                     | 55                 | .0023              | .584                     | 47                 | 60                      |



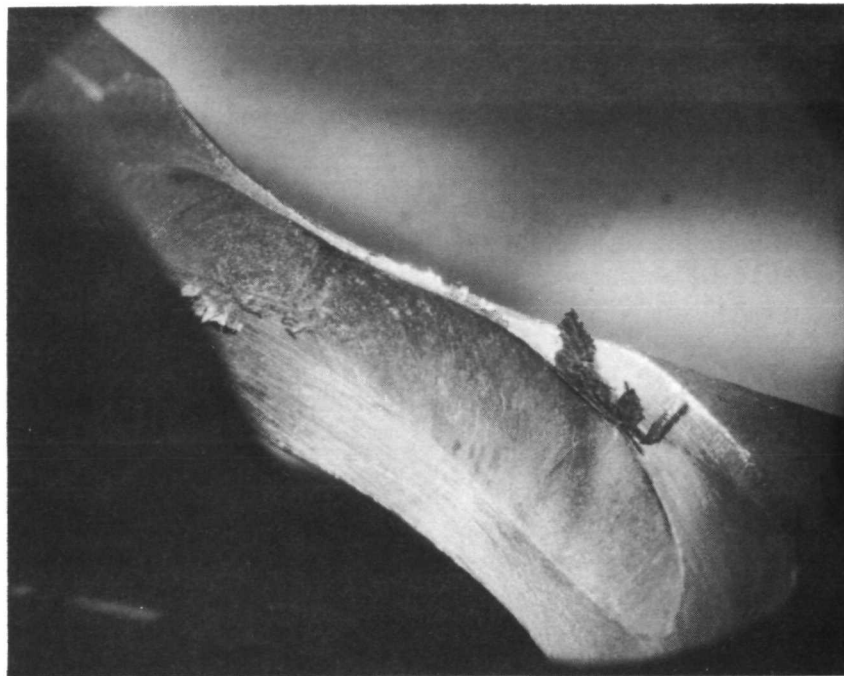
#### VIII, C, One-Hour Bearing Evaluation Tests in FLOX (cont.)

tests, 2 and 3, the bearings operated for the scheduled one-hour duration. Comparing these data with the one-hour tests in liquid fluorine shows that ball and race wear was approximately 25% of that experienced in fluorine. The Berylco Nickel 440 ball pocket wear was comparable and is illustrated in Figure 24. As can be noted in the figure, metal particles generated by wear in the cage ball pockets were sometimes quite appreciable in size.

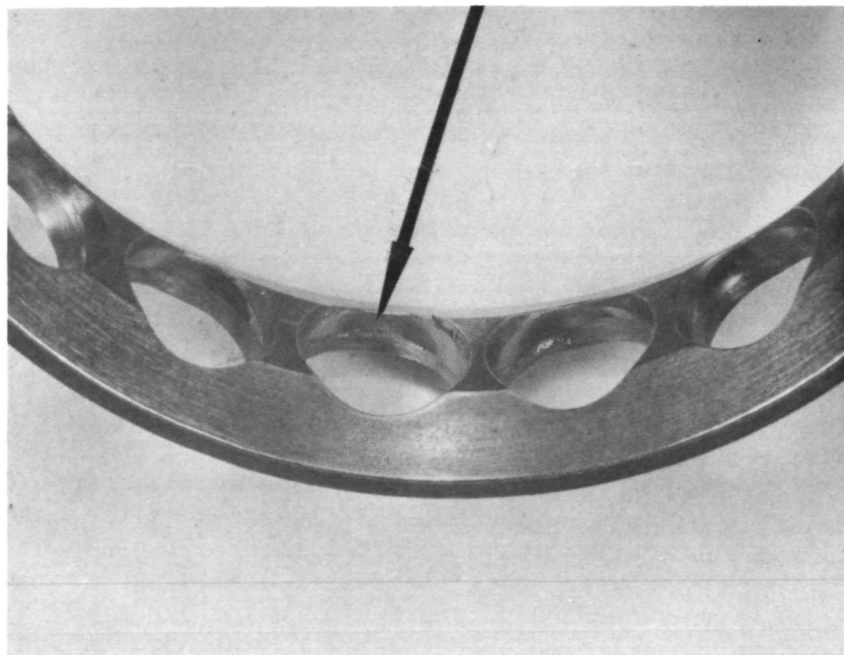
Since load speed and bearing geometry were identical in both Task IV and Task V tests, it is presumed that the mechanical parameters of the bearing were identical, i.e., contact angle, surface compressive stress, cage rubbing velocity, ball spin, etc., were the same for each test series. Therefore "mechanical" wear, idealized as a function of rubbing velocity, load, and the ball, race and cage materials should be identical. Velocities and loads were maintained, however, the lubricating material formed may have been different due to the presence of oxygen in the FLOX.

Either of two, opposite, wear mechanisms could be promoted by different surface chemistry. On the one hand, the mixed iron oxy-halide salts are known to be more volatile and, therefore, should be less adherent to the base metal than iron difluoride. In this hypothesis, it is assumed that the shear strength of the mixed salts is appreciably less than the iron difluoride and, therefore, will wear away in increments each less than the thickness of the total surface layer. However, the iron fluoride film being stronger does not wear away in layers but is spalled away from the parent metal. The second wear mechanism is based on the spalling removal of the entire fluoride film, the thickness of which is dependent on the reaction rate of the test fluids with the bearing ball/race material. Since FLOX is less reactive than liquid fluorine (by dilution with oxygen), the rate of iron difluoride formation would be reduced and, hence, less bearing wear.

Both mechanisms neglect the effect of metallic films transferred from the cage to the ball/race contact area. Since the cage wear in FLOX was comparable to that in liquid fluorine, it is assumed that the metallic fluorides were transferred to the ball/race contact area at the same rate. Then a corollary to this assumption is that the fluorides of the cage material are not the controlling lubrication factor. Metal fluorides did provide effective lubrication in the NASA seal work (Ref 4) at a sliding velocity of 2300 fpm (11.7 m/sec) and contact face pressure of 2 psi ( $13.8 \times 10^3$  N/m<sup>2</sup>). Therefore one must look at the differences between the seal and bearing testing. First the bearing sliding velocities were about three times the seal sliding velocity. Second, the ball-to-race contact loading was approximately 75,000 times the seal contact pressure. Third, the ball spin is unique to the ball bearing.



8X



2X

Figure 24. Ball Pocket Wear Scar, Berylco Nickel 440,  
Task IV Test 2 in FLOX

## VIII, Test Data Analysis (cont.)

### D. PRACTICAL CONSIDERATIONS OF THE TEST RESULTS

Successful operation of bearings in a test program and adequate bearing performance in a rocket engine turbopump are not necessarily synonymous. First, duplication of operating conditions is unlikely. Second, in a test program, successful operation is often interpreted as meaning no fatigue or cage failure resulting in bearing lockup. The wear life of a bearing is not defined. Data from this program has demonstrated that the bearings can function despite a large amount of wear. Wear of the degree experienced probably would be unacceptable for bearings supporting a high speed rotor because of the increased whirl forces and change in critical speed resulting from the increased bearing clearance.

Figures 25, 26 and 27 show the variation in operating contact angle, axial play and radial spring rate of the Task II bearing design as a function of ball wear. These curves neglect the influence of race curvature change (which would almost double the clearance), since the intent is illustrative. The ball wear alone measured after the one-hour-duration Task IV tests could cause contact angle changes of  $10^\circ$  to  $30^\circ$  and a decrease in spring constant of 600%. Typical rotor dynamics are illustrated in Figure 28 as a function of bearing spring constant. Since most lightweight turbopumps require operation in the "flexible mounting operation" zone, or close to the "knee" of the curves, 600% bearing stiffness variations obviously cannot be tolerated. Even smaller (10% - 20%) increases in clearance could produce drastic changes in bearing spring rate and critical speed margin.

### Bearing Geometry (New)

Curvature Inner 52%  
 Curvature Outer 54%  
 Free Contact Angle 29°  
 Ball Diameter 0.4375 in. (0.0111m)  
 Ball Complement 16

### Operating Conditions

Speed 20,000 RPM  
 Axial Load 1160 lb (5200N)  
 Radial Load 0

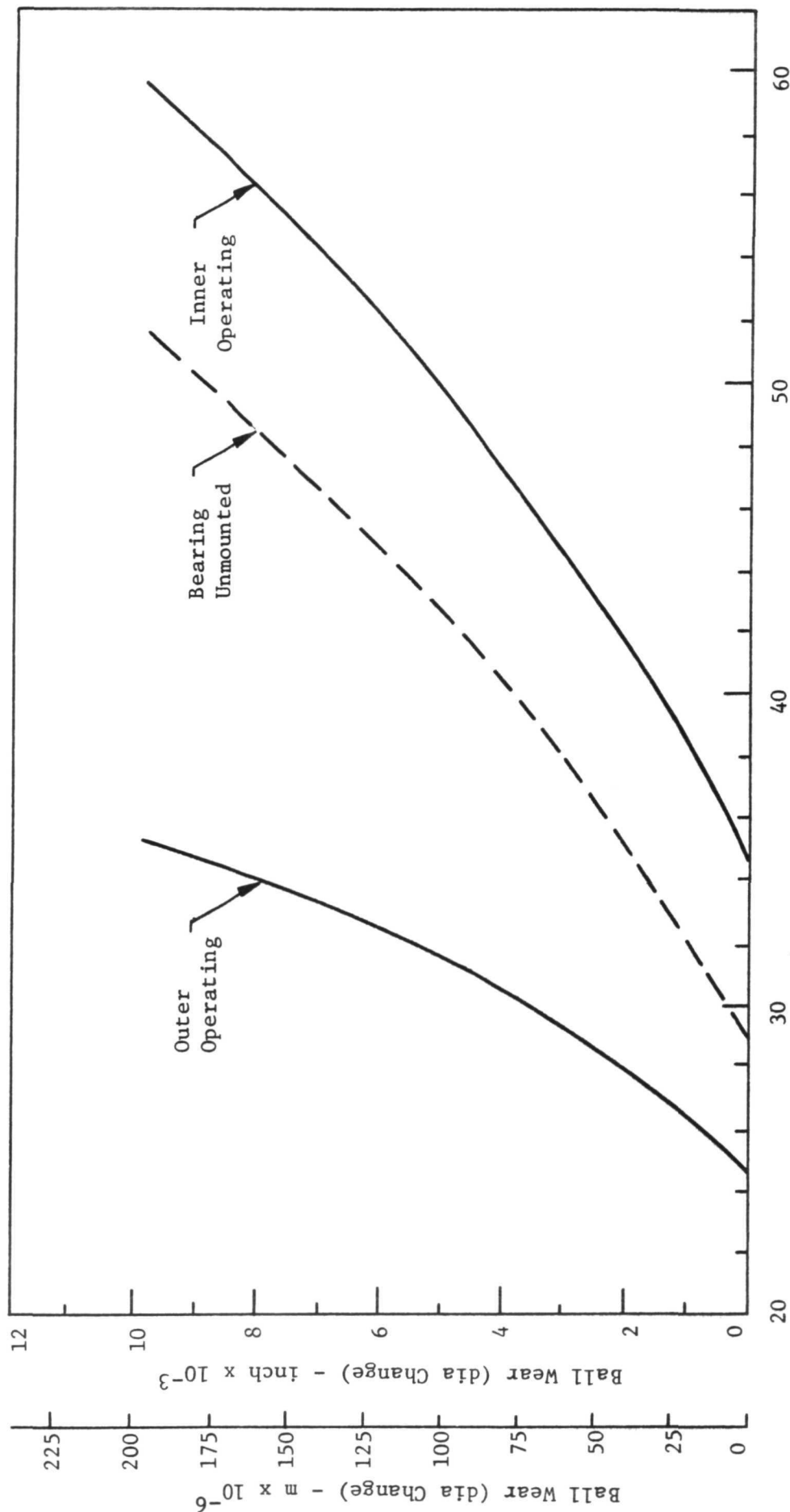


Figure 25. Operating Contact Angles vs Ball Wear

# Bearing Geometry (New)

|                    |                      |
|--------------------|----------------------|
| Curvature Inner    | 52%                  |
| Curvature Outer    | 54%                  |
| Free Contact Angle | 29°                  |
| Ball Diameter      | 0.4375 in. (0.0111m) |
| Ball Complement    | 16                   |

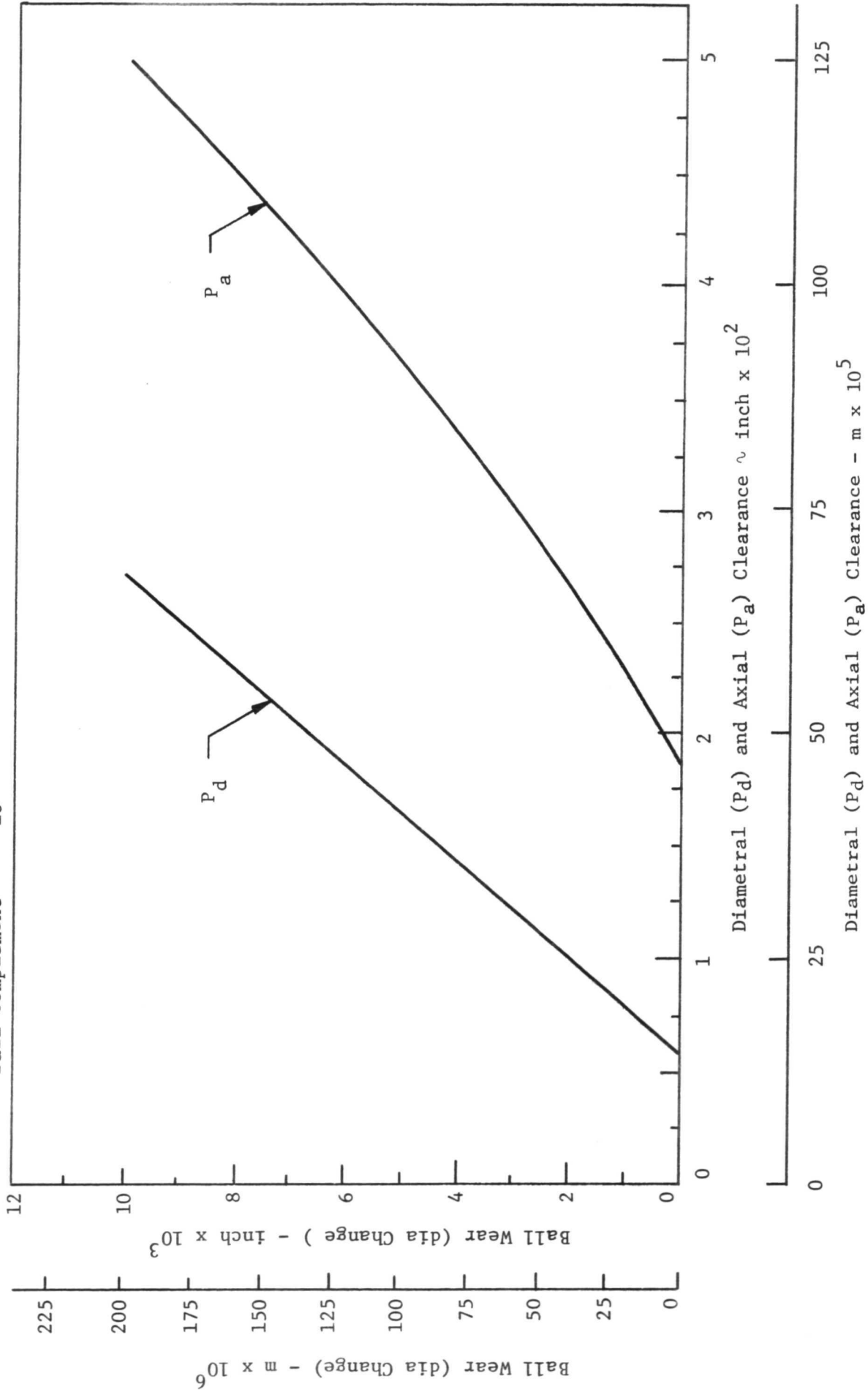


Figure 26. Internal Clearance vs Ball Wear

Bearing Geometry (New)

Curvature Inner 54%  
 Curvature Outer 52%  
 Free Contact Angle 29°  
 Ball Diameter 0.4375 in. (0.0111lm)  
 Ball Complement 16

Operating Conditions

Speed 20,000 RPM  
 Axial Load 1160 lb (5200N)  
 Radial Load 250 lb, 750 lb  
 (1120N), (3360N)

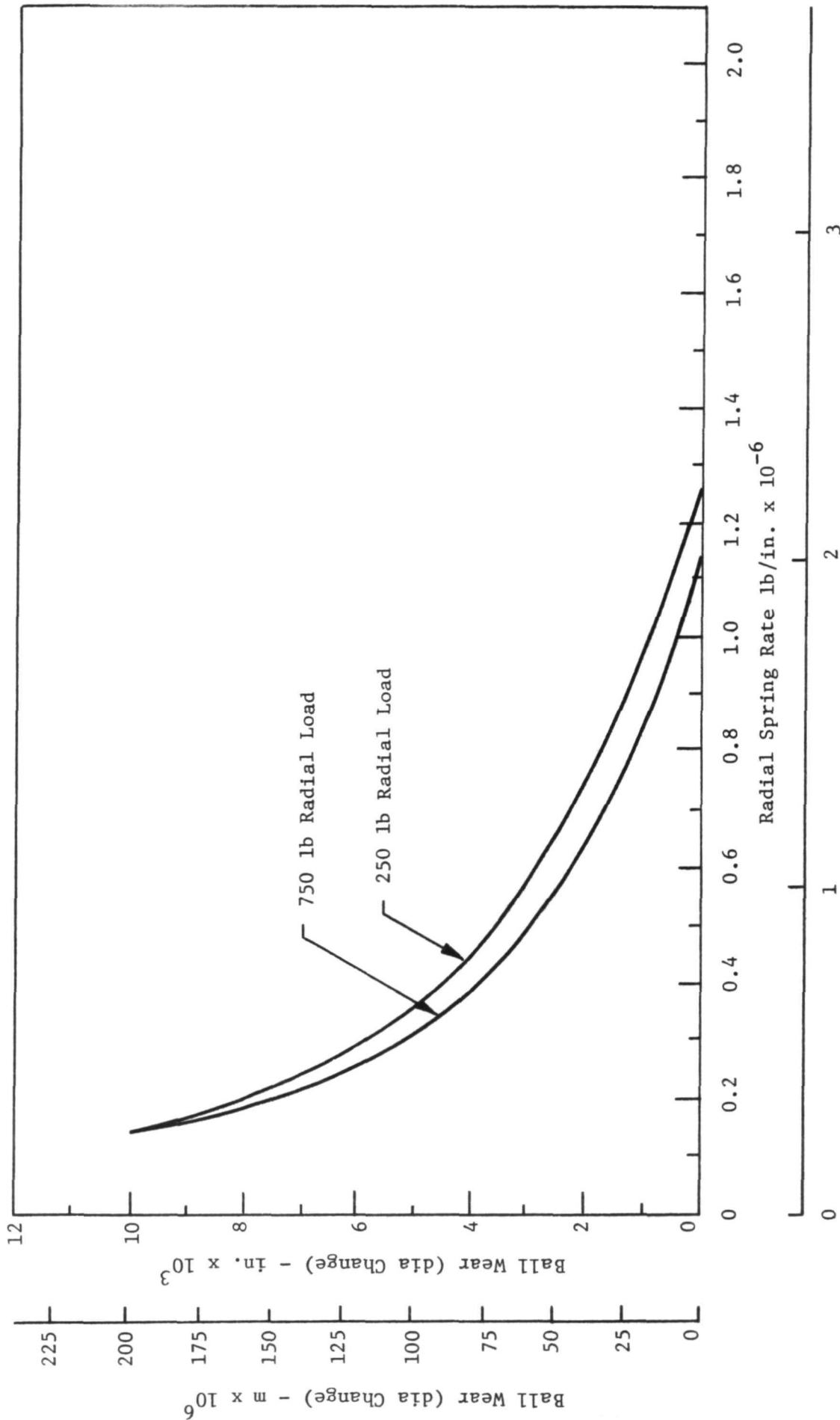


Figure 27. Radial Spring Rate vs Ball Wear

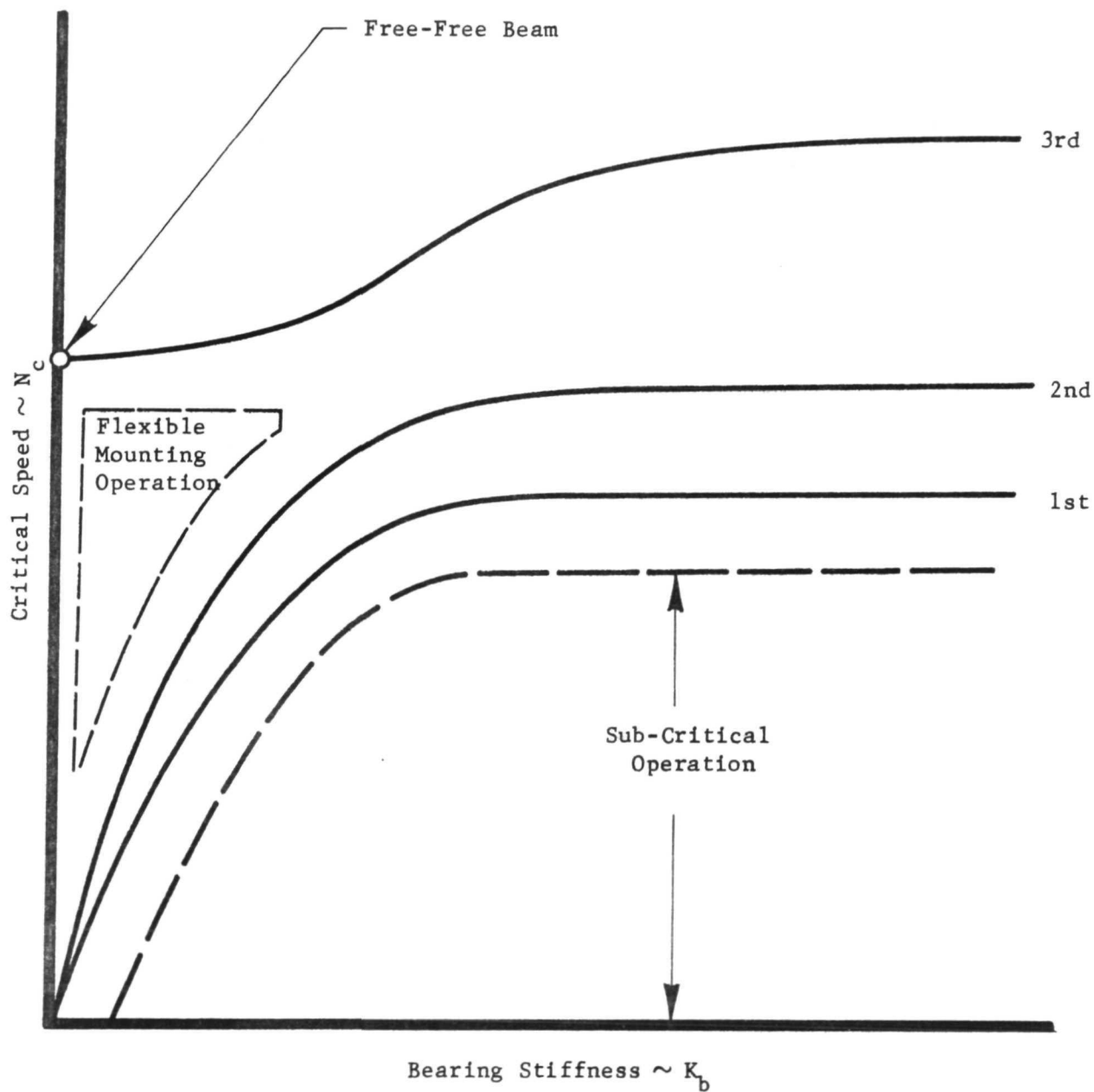


Figure 28 -- Rotor Dynamic Characteristics as a Function of Bearing Stiffness

## IX. TESTER, TEST SETUP, AND TEST PROCEDURES

### A. TESTER AND SETUP

The bearing tester and drive unit is shown installed in the test setup in Figure 29. Power from the turbine drive unit, shown in Figure 30, was transmitted to the test bearing shaft through a flexible, disc-type, coupling. This coupling physically separated the oil-lubricated drive assembly from the cryogenic bearing tester and allowed for thermal expansion of both the hot and cold assemblies without restraint.

The bearing tester, which is shown in Figure 31, was designed so that the test bearings and shaft assembly could be easily removed as a cartridge. This permitted all of the test plumbing, mounting structure and instrumentation to remain intact. The tester and turbine drive assembly alignment also remained undisturbed. This test bearing exchange feature permitted rapid "turn-around" of the test hardware.

The test bearing-shaft cartridge slipped into an inner housing which, in turn, was mounted on a large trunion bearing (see Figure 31). Test bearing torque was transmitted from the inner housing via a rod to an externally mounted load cell. This torque readout system was selected over other types because it was independent of plumbing and other instrumentation. Also, it required no heavy slip ring assemblies. Unfortunately, it was not known that fluoride salts would build up in the trunion bearings and would interfere with the torque reading. In fact, these salts eventually eliminated any reading other than a bearing failure reading. It was discovered that the fluoride salt buildup was sensitive to flow velocity; there was little or no salt buildup in close clearance, high flow velocity areas, while there was heavy salt buildup in larger low flow velocity areas such as the trunion bearing cavities. Consequently, torque readings had to be disregarded and the system became a failure monitoring system.

Both the torque rod and the tester input shaft openings incorporated non-contacting labyrinth seals that were purged with helium gas to prevent fluorine leakage. The input shaft labyrinth seal system also had an outer nitrogen gas purged area to minimize the external leakage of helium from the inner purged area. The labyrinth purge seal arrangement was used to eliminate any problems that might have occurred with the use of an undeveloped rubbing contact sealing system. Also, rubbing contact seals would have added parasitic drag which would have decreased torque readout sensitivity.

The bearings were axially loaded by a piston that was pressurized by the liquid fluorine. The load was a function of the pressure differential across the piston (liquid fluorine supply pressure less the test bearing cavity pressure). This differential, and thus the bearing coolant flow rate, was controlled by an orifice in the piston. The load was transmitted through the first test bearing into the shaft and then through the second test bearing into the inner housing. The first bearing load was equal to the piston area times the piston  $\Delta P$ . The second bearing load was higher by an amount equal to the shaft area times the bearing cavity pressure.



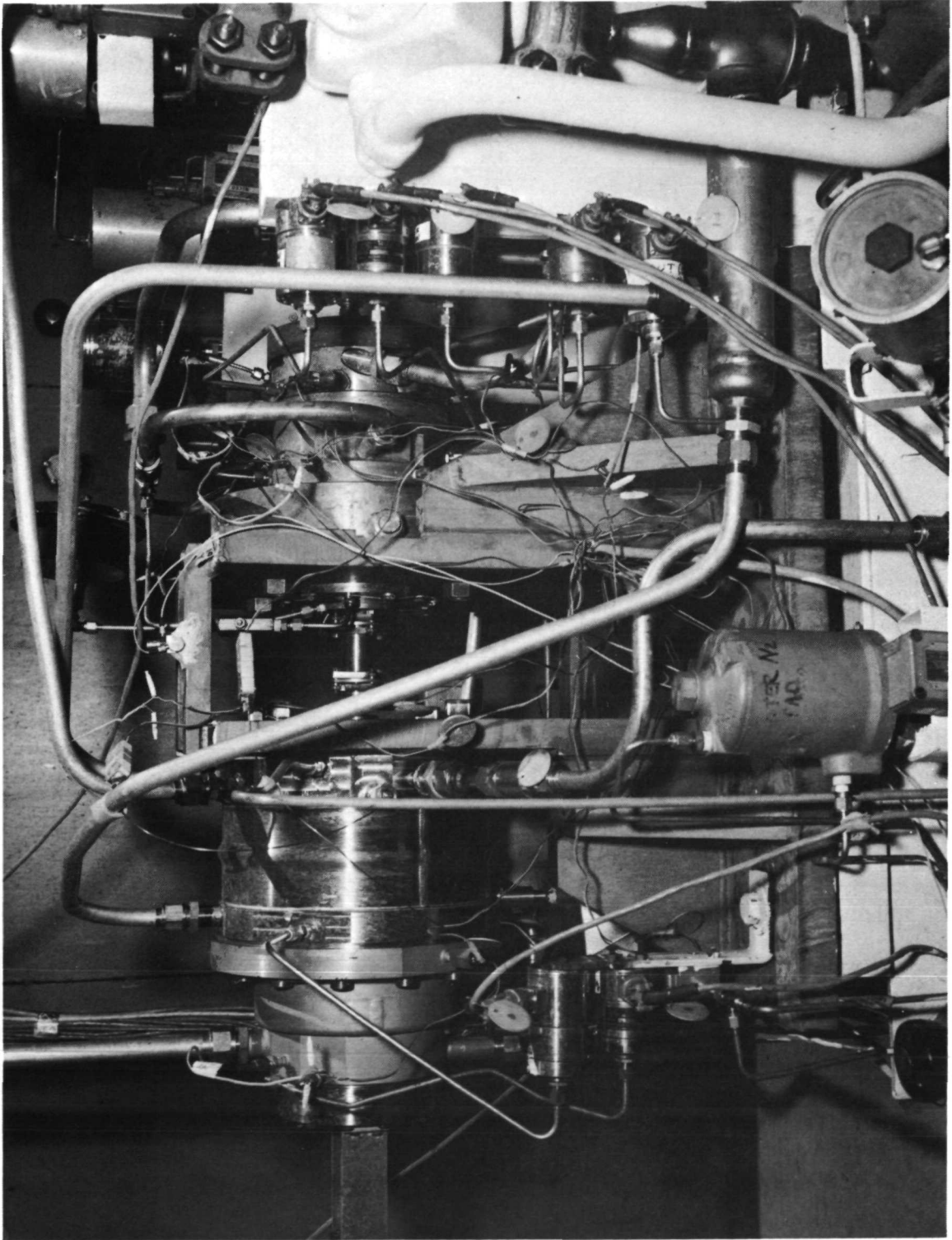


Figure 29. Tester and Drive Assembly in Test Setup

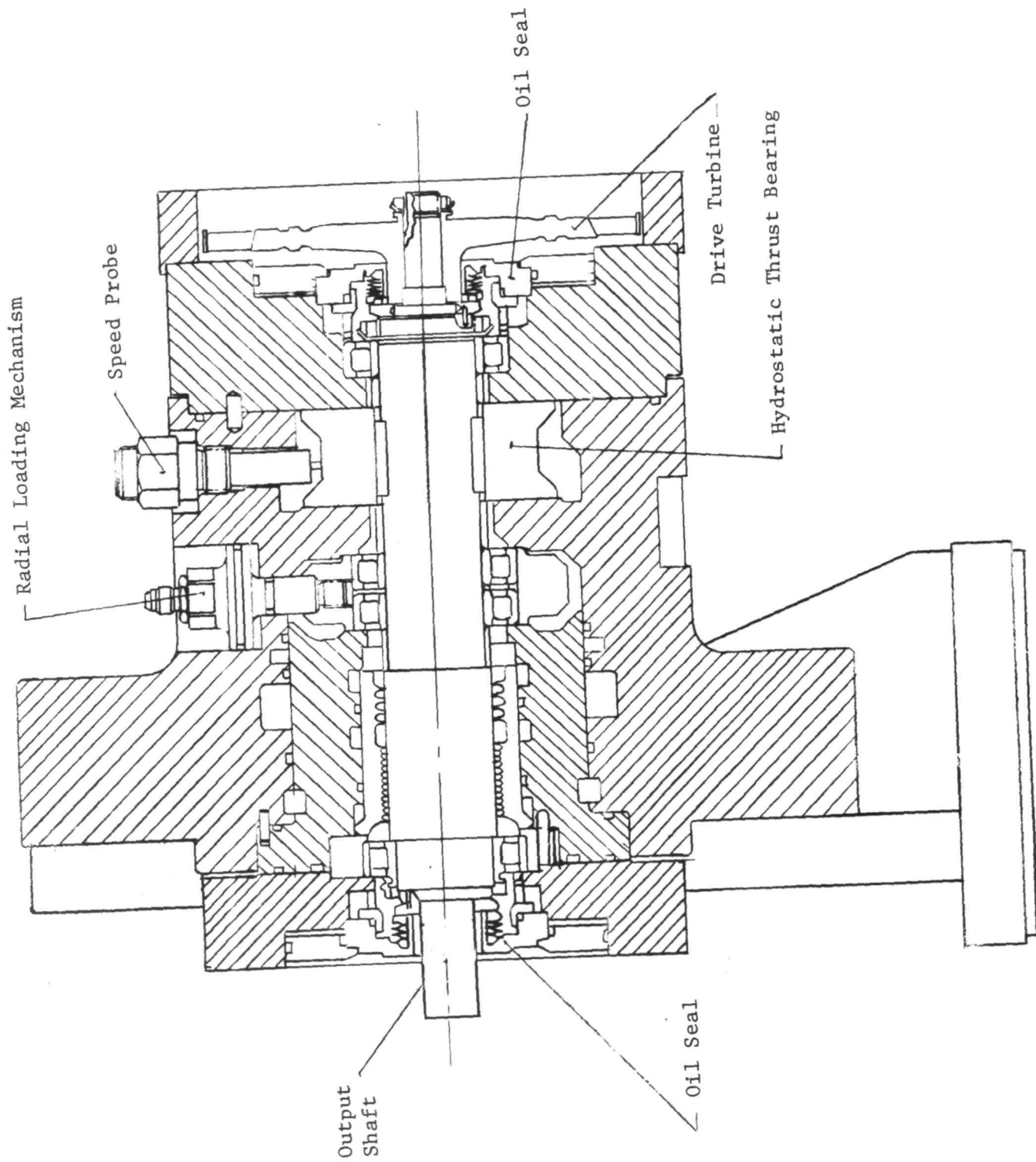


Figure 30. Turbine Drive Assembly

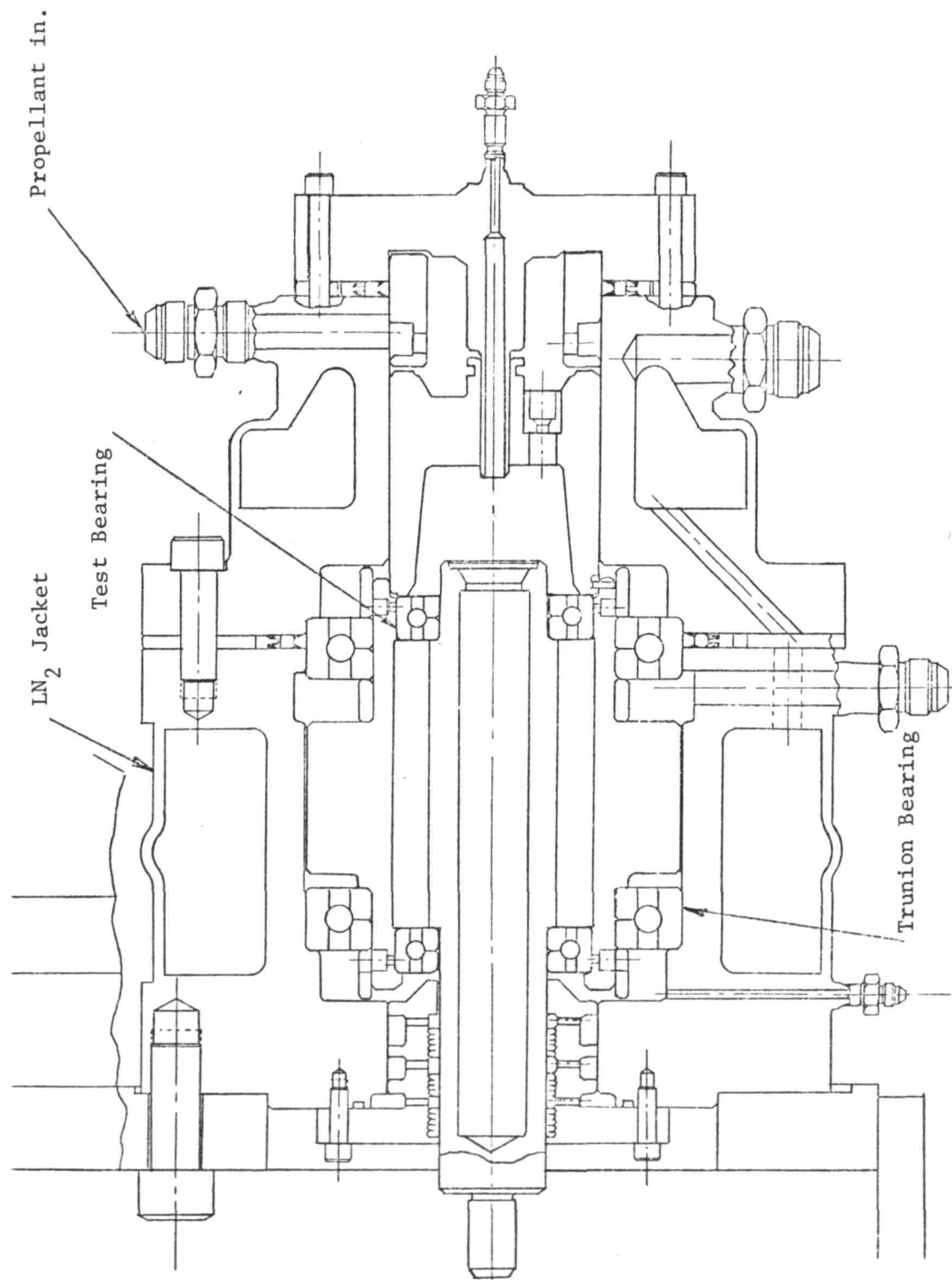


Figure 31. Bearing Tester Assembly

## IX, A, Tester and Setup (cont.)

The tester was equipped with a liquid nitrogen jacket which was installed in series with the piping jacket. Prechilling the tester and associated piping prevented excessive vaporization of the liquid fluorine during the initial tester bleed-in. The liquid nitrogen chill was maintained during the entire test.

The liquid fluorine flow for bearing cooling was controlled by a removable orifice in the load piston and the pressure differential across this orifice. Parasitic flow around the load piston was minimized by reducing the piston housing clearance. This clearance was decreased from 0.006 to 0.002 in. ( $15.24 \times 10^{-5}$  to  $5.08 \times 10^{-5}$  m) at the completion of the Task I material evaluation tests. The change made possible an increased run duration for the Task IV and Task V tests.

The propellant system consisted of a conventional pressure-fed flow loop with triple-wall run and catch vessels. Liquid fluorine flowed from a 1000 gal ( $3.785 \text{ m}^3$ ) run tank through the bearing tester to a 1000 gal ( $3.785 \text{ m}^3$ ) catch tank. A charcoal pit burner was utilized to burn off all fluorine gases vented from the catch tank during a test and purged from the flow loop after a test. A schematic of the test setup is shown in Figure 32.

### B. TEST AND POST TEST PROCEDURES

The following sequence was followed for installation, test, and inspection:

The bearing tester was cleaned prior to installation and passivated with gaseous fluorine prior to the first test in each task. A gaseous nitrogen purge was maintained at all times that the tester was on standby.

The assembled test bearing shaft was cleaned and then passivated with gaseous fluorine in accordance with the approved procedure. A separate passivation chamber was provided for this purpose.

The shaft subassembly was installed into the tester assembly. Clean polyethylene gloves were used by all personnel when handling the passivated shaft. In addition, the shaft was placed in a polyethylene bag to maintain cleanliness and minimize exposure to the moisture from the air.

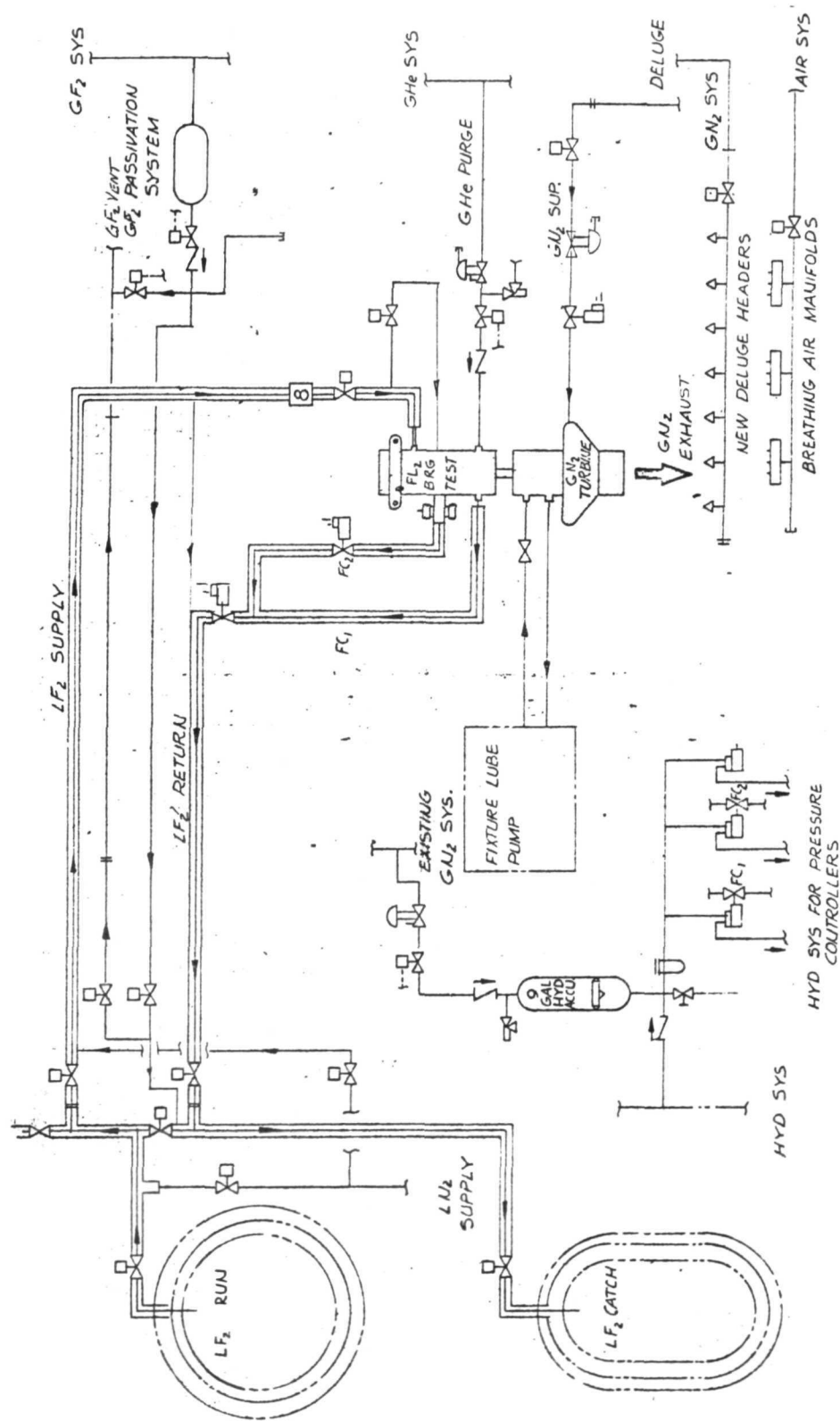


Figure 32. Bearing Test Position Schematic

## IX, B, Test and Post Test Procedures (cont.)

A pretest leakage check was performed at 50 psig ( $3.45 \times 10^5 \text{ N/m}^2$ ) using gaseous helium as the pressurant. Leakage was not to exceed a 5 psi ( $3.45 \times 10^4 \text{ N/m}^2$ ) pressure decay in 15 minutes. If the leakage exceeded this value, the cavity between the double seals was purged with gaseous helium at a pressure  $\approx$  15 psi ( $10.34 \times 10^4 \text{ N/m}^2$ ) greater than the fluorine or the seals were replaced.

Gaseous fluorine was bled into the tester assembly. An approved pressure time schedule was followed to ensure additional passivation during the bleed-in process.

Locate wear areas in the cage pockets to determine operating dynamics.

Make wear scar determination of each cage.

Remeasured the ball diameters.

Obtain micrographs of distressed areas to provide a permanent record of the material surface condition.

Dye penetrant inspect balls and races.

X. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1. Bearing wear to the degree experienced during the one-hour tests in liquid fluorine would not be acceptable for a reusable rocket engine turbopump.
2. None of the ball separator materials tested provided effective lubrication.
3. Bearing wear in fluorine was both chemical and mechanical.
4. Bearing wear was not reduced by a ball unloading chute.
5. Ball bearing wear was less in 82.6% FLOX than in liquid fluorine.
6. Bearing failures in fluorine are possible without catastrophic results if shutdown is rapid enough.

B. RECOMMENDATIONS

1. Harder race and ball materials, such as carbides, should be considered for longer wear life.
2. Noncontacting hydrostatic bearings should be considered as an alternative bearing for turbopumps operating in liquid fluorine.

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