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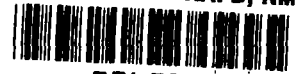
**RESEARCH AND DEVELOPMENT
OF HIGH TEMPERATURE GAS BEARINGS**

**II - Selection and Evaluation of Gas Bearing Materials
in Argon at 900 F and 1400 F**

by S. F. Murray

Prepared by
MECHANICAL TECHNOLOGY INCORPORATED
Latham, N. Y.
for Lewis Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • DECEMBER 1969



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Prepared under Contract No. NAS 3-9433 by
MECHANICAL TECHNOLOGY INCORPORATED
Latham, N.Y.

for Lewis Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION



FOREWORD

The research described herein, which was conducted by Mechanical Technology Incorporated under NASA Contract NAS 3-9433, was performed under the project management of Mr. Henry B. Tryon, Space Power Systems Division, NASA Lewis Research Center. The report was originally issued as Mechanical Technology Incorporated Report MTI-69TR22, volume II.

TABLE OF CONTENTS

	<u>Page</u>
LIST OF TABLES	vii
LIST OF FIGURES	viii
SUMMARY OF RESULTS	xi
1.0 INTRODUCTION	1
2.0 APPROACH TO THE PROBLEM	3
2.1 The Use of Coatings	3
2.2 Evaluation Test Techniques	6
2.3 Previous Experience on Coatings	7
2.4 Candidate Materials for High Temperature Bearing Coatings	9
3.0 TEST EQUIPMENT AND TEST PROCEDURE	13
3.1 Test Rig	13
3.2 Instrumentation	14
4.0 TEST PROCEDURE	17
4.1 Start-Stop Low Speed Sliding Tests	17
4.2 High Speed Rubs Under Shock Loads	18
5.0 TEST RESULTS	21
5.1 Start-Stop Tests	21
5.1.1 900 F Tilting Pad Journal Bearing - Start-Stop Tests ..	22
5.1.2 1400 F Tilting Pad Journal Bearing - Start-Stop Tests ..	23
5.1.3 900 F Thrust Bearing - Start-Stop Tests	24
5.1.4 1400 F Thrust Bearing - Start-Stop Tests	29
5.2 High Speed Rub Tests	32
5.2.1 900 F Tilting Pad Journal Bearing Tests at High Speed ..	33
5.2.2 1400 F Tilting Pad Journal Bearing Tests at High Speed ..	35
5.2.3 900 F Thrust Bearing Tests at High Speed	36
5.2.4 1400 F Thrust Bearing Tests at High Speed	38
6.0 DISCUSSION OF RESULTS	40
7.0 RECOMMENDATIONS FOR FUTURE WORK	43
REFERENCES	45
TABLES	46
FIGURES	
APPENDIX A - TASK III Bearing Materials Screening Study	

TABLE OF CONTENTS (CON'T)

APPENDIX B - PREPARATION OF TEST SPECIMENS AND DIMENSIONAL STABILITY
TEST RESULTS

MTI SPECIFICATION #29 - Application of Ceramic and Cermet
Coatings to the Surface of Bearings and Shafts

LIST OF TABLES

Page

TABLES IN MAIN TEXT

TABLE 1	Material Combinations Which Were Used in Early Gas Bearing Work	46
TABLE 2	Summary of Results on Start-Stop Tests Tilting Pad Journal Bearings at 900 F in Argon	47
TABLE 3	Surface Profile Measurements on Start-Stop Specimens Tilting Pad Journal Bearings at 900 F in Argon	48
TABLE 4	Summary of Results on Start-Stop Tests Tilting Pad Journal Bearings at 1400 F in Argon	49
TABLE 5	Surface Profile Measurements on Start-Stop Specimens Tilting Pad Journal Bearings at 1400 F in Argon	50
TABLE 6	Summary of Results of Start-Stop Tests Thrust Bearings at 900 F in Argon	51
TABLE 7	Summary of Results of Start-Stop Tests Thrust Bearings at 1400 F in Argon	52
TABLE 8	Summary of Results of High Speed Rub Tests Tilting Pad Journal Bearing Tests at 900 F in Argon	53
TABLE 9	Surface Profile Measurements of High Speed Rub Specimens Tilting Pad Journal Bearing Tests at 900 F in Argon	54
TABLE 10	Summary of Results of High Speed Rub Tests Tilting Pad Journal Bearing Tests at 1400 F in Argon	55
TABLE 11	Summary of Results of High Speed Rub Tests Thrust Bearing Tests at 900 F in Argon	56
TABLE 12	Surface Profile Measurements of High Speed Rub Specimens Thrust Bearing Tests at 900 F in Argon	57
TABLE 13	Summary of Results of High Speed Rub Tests Thrust Bearing Tests at 1400 F in Argon	58
TABLE 14	Surface Profile Measurements of High Speed Rub Specimens Thrust Bearing Tests at 1400 F in Argon	59

TABLES IN APPENDIX A

TABLE A-1	Materials Under Consideration at 900 F	108
TABLE A-2	Materials Under Consideration at 1400 F	109
TABLE A-3	Candidate Foil Materials	110

TABLES IN APPENDIX B

TABLE B-1	Test Materials Source and Heat Treatments	116
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LIST OF FIGURES

FIGURES IN MAIN TEXT

- FIG. 1 Contact Surfaces on Tilting-Pad Bearing and Shaft After High Speed Rubs. Chrome Oxide Coated Pad vs Chrome Oxide Coated Journal. Run in Argon at 60,000 rpm. Test Temperature 500 F.
- FIG. 2 Contact Surfaces on Tilting-Pad Bearing and Journal After High Speed Rubs. Nickel Bonded Tungsten Carbide Coated Pad vs Al_2O_3 Coated Shaft. Run in Argon at 60,000 rpm. Test Temperature 350 F.
- FIG. 3 Surface of Tilting Pad Bearing After 100 High Speed Rubs at 48,000 rpm in Ambient Air. Bearing Coating: 0.003" chrome oxide plus 0.0001" resin-bonded MoS_2 .
- FIG. 4 Chrome Oxide Coated Hydrodynamic Journal and Tilting Pad Bearings from Navy Shock Test Machine After 1400 Impacts. Bearing Still Functioning Satisfactorily.
- FIG. 5 Surface Appearance of Chrome Oxide Coated Pads with Different Density Coatings. Both Pads Subjected to One Hundred High Speed Rubs at 48,000 rpm in Air.
- FIG. 6 "Layout Drawing of High Temperature Hydrodynamic Bearing Test Rig for Materials Evaluations".
- FIG. 7 Partially Assembled View of Test Rig Set Up for Tilting Pad Journal Bearing Evaluations. Enclosure for Argon Blanketing is Not Shown.
- FIG. 8 View of Partially Assembled Test Rig Set Up for Thrust Bearing Evaluations. One Side of the Enclosure has been Removed.
- FIG. 9 Overall View of Test Rig Set Up for Thrust Bearing Evaluations in an Argon Environment.
- FIG. 10 Chrome Oxide Coated Tilting Pad Bearing vs. Chrome Oxide Coated Journal. After 1000 Starts and Stops at 900 F in Argon.
- FIG. 11 Al_2O_3 Coated Tilting Pad Bearing vs Tungsten Carbide Coated Journal. After 1000 Starts and Stops at 900 F in Argon.
- FIG. 12 Al_2O_3 Coated Tilting Pad Bearing vs Uncoated Cold-Worked Haynes 25 Journal. Failed After 180 Starts and Stops at 900 F in Argon.
- FIG. 13 Al_2O_3 Coated Tilting Pad Bearing vs Stellite Coated Journal. After 1000 Starts and Stops at 1400 F in Argon.
- FIG. 14 Al_2O_3 Coated Tilting Pad Bearing vs Chrome Carbide Coated Journal. After 1000 Starts and Stops at 1400 F in Argon.

FIGURES IN MAIN TEXT (CON'T)

- FIG. 15 Uncoated Rene 41 Tilting Pad Bearing vs Fluoride Film Coating on Rene 41 Journal. After 1000 Starts and Stops at 1400 F in Argon.
- FIG. 16 Chrome Oxide Coated Grooved Thrust Bearing vs Chrome Oxide Coated Thrust Collar. Failed After 615 Starts and Stops at 900 F in Argon. Final Stress 1 psi.
- FIG. 17 Tungsten Carbide Coated Grooved Thrust Bearing vs Al_2O_3 Coated Thrust Collar. Completed 1000 Starts and Stops at 1.5 psi Stress in Argon at 900 F.
- FIG. 18 Al_2O_3 Coated Grooved Thrust Bearing vs Uncoated Cold-Worked Haynes 25 Thrust Collar. Failed After 60 Starts and Stops at 900 F in Argon. Final Stress 1 psi.
- FIG. 19 Chrome Carbide Coated Grooved Thrust Bearing vs Al_2O_3 Coated Collar. Completed 1000 Starts and Stops at 2.5 psi Stress and an Additional 270 Starts and Stops at 3.2 psi. in Argon at 900 F.
- FIG. 20 Chrome Carbide Coated Grooved Thrust Bearing vs Al_2O_3 Coated Thrust Collar. Both Surfaces were Coated with Solid Lubricant Film and Subsequently Lapped. Completed 1000 Starts and Stops at 1.4 psi at 1400 F in Argon.
- FIG. 21 Stellite 6 Coated Grooved Thrust Bearing vs Al_2O_3 Coated Thrust Collar. Failed After 90 Starts and Stops at 1 psi in Argon at 1400 F.
- FIG. 22 Nickel-Chrome Alloy Coated Grooved Thrust Bearing vs Eutectic Fluoride Coating on Rene 41 Thrust Collar. Would Not Carry 2 psi after 590 Start-Stop Cycles at 1400 F in Argon.
- FIG. 23 Chrome Oxide Coated Tilting Pad Bearing vs Chrome Oxide Coated Journal. After High Speed Rubs at 900 F in Argon.
- FIG. 24 Al_2O_3 Coated Tilting Pad Bearing vs Tungsten Carbide Coated Journal. After High Speed Rubs at 900 F in Argon.
- FIG. 25 Al_2O_3 Coated Tilting Pad Bearing vs Uncoated Cold-Worked Haynes 25 Journal. After High Speed Rubs at 900 F in Argon.
- FIG. 26 Al_2O_3 Coated Tilting Pad Bearing vs Chrome Carbide Coated Journal. After High Speed Rubs at 900 F in Argon.
- FIG. 27 Tilting Pad Bearings and Journals. After High Speed Failures at 1400 F in Argon.
- FIG. 28 Tungsten Carbide Coated Grooved Thrust Bearing vs Al_2O_3 Coated Thrust Collar. After High Speed Rubs at 900 F in Argon at 38,500 rpm.
- FIG. 29 Chrome Oxide Coated Grooved Thrust Bearing vs Chrome Oxide Coated Thrust Collar. After High Speed Rubs at 900 F in Argon at 38,500 rpm.

FIGURES IN MAIN TEXT (CON'T)

- FIG. 30 Al_2O_3 Coated Grooved Thrust Bearing vs Cold-Worked Haynes 25 Thrust Collar. After High Speed Rubs at 900 F in Argon at 38,500 rpm.
- FIG. 31 Chrome Carbide Coated Grooved Thrust Bearing vs Al_2O_3 Coated Thrust Collar. After High Speed Rubs at 900 F in Argon, 38,500 rpm.
- FIG. 32 Chrome Carbide Coated Grooved Thrust Bearing vs Al_2O_3 Coated Thrust Collar. After High Speed Rubs at 1400 F in Argon at 38,500 rpm.
- FIG. 33 Nickel-Chrome Groove Pattern on Rene 41 Thrust Bearing vs $\text{BaF}_2/\text{CaF}_2$ Eutectic on Rene 41 Thrust Collar. After High Speed Rubs at 1400 F in Argon at 38,500 rpm.

FIGURES IN APPENDIX A

- FIG. A-1 Overall View of Groove Pattern and Close-Up Showing Groove Detail. Grooves Formed by Plasma-Spraying Cr_2O_3 Through a Metal Mask.

FIGURES IN APPENDIX B

- FIG. B-1 Set-Up Used for Spraying Groove Patterns.
- FIG. B-2 Microstructure of AISI 4340 Steel Before and After 100 Hours at 900 F.
- FIG. B-3 Microstructure of A-286 Stainless Before and After 100 Hours at 900 F.
- FIG. B-4 Microstructure of Cold-Worked Haynes 25 Before and After 100 Hours at 900 F.
- FIG. B-5 Microstructure of TZM Molybdenum Before and After 100 Hours at 900 F.
- FIG. B-6 Microstructure of TD Nickel Before and After 100 Hours at 1400 F.
- FIG. B-7 Microstructure of Rene 41 Before and After 100 Hours at 1400 F.
- FIG. B-8 Microstructure of Solution Treated Haynes 25 Before and After 100 Hours at 1400 F.

SUMMARY OF RESULTS

A high temperature experimental study was made to evaluate the effect of sliding contacts on the hydrodynamic behavior of tilting pad journal bearings and on spiral grooved thrust bearings. Both start-stop and high speed rub tests were run in an argon environment at two temperatures, 900 F and 1400 F. Major emphasis was placed on the use of plasma coatings to provide wear resistant surfaces.

The table at the end of this summary presents an overall compilation of these evaluations. The results showed that a plasma sprayed Al_2O_3 coating sliding against a nickel-chrome bonded chrome carbide coating was the best combination for use on both thrust and journal bearings in an inert environment in this temperature range.

The problem of selecting materials for good sliding behavior in the 900 F to 1400 F range is much more difficult than it was at temperatures up to 500 F. For reliable start-stop operation of thrust bearings, without hydrostatic jacking, design stresses may have to be limited to about 2.5 psi unless better materials or solid lubricant films are found.

Several interesting observations were made in these tests. These include the following:

1. In only one test was a bond failure between the coating and the substrate observed. This was on a tilting pad bearing which seized on the journal at 1400 F and at a speed of 30,000 rpm. The plasma-sprayed groove patterns were no problem as far as chipping or flaking was concerned. Groove damage was always manifested as surface damage or wear rather than separation of the coating from the substrate.
2. High speed rub tests on chrome oxide coatings at 900 F showed smooth but high wear, much worse than the wear observed at 500 F.
3. Preliminary evaluations of the dimensional stability of the candidate

substrate materials showed that dimensional stability could be a problem, even at 900 F, unless better heat treatments and aging procedures are developed. These dimensional stability tests are described in Appendix B of this report.

4. Stellite coatings in argon at 1400 F were much poorer from a sliding standpoint than they were in air at the same temperature. This indicates that oxide films are essential for good sliding behavior with this class of alloys.
5. The NASA eutectic fluoride film was effective in preventing surface damage, but several problems were encountered in using this film, and more development effort is required.
6. When different coatings were used for the bearing and journal surfaces, it was anticipated that interchanging these coatings would have an effect on sliding behavior. However, in these tests it was not clearly shown whether or not certain pairs of coatings performed differently if the journal and bearing pad coatings were interchanged.
7. In view of the very good results obtained with the Al_2O_3 coating sliding against a nickel-chrome bonded chrome carbide coating, further investigation aimed at establishing the optimum chrome carbide composition, as well as evaluation of the combination of chrome carbide against itself, is strongly recommended. This is discussed further in the Recommendations section of this report.

OVERALL SUMMARY OF BEARING EVALUATIONS IN ARGON

TEST TEMPERATURE - 900 F.

Material Combination (a)	Type of Bearing	Type of Test (b)	Result (d)	Relative Ranking (c)
Chrome oxide* vs. Chrome oxide*	Tilting Pad	S-S	Completed 1000 cycles at 4 psi.	A
		H.S.	Failed after 18 drops of 3 lbs.	B
Al ₂ O ₃ * vs. Tungsten Carbide*	Thrust Bearing	S-S	Failed after 615 cycles	B - C
		H.S.	Completed test without failing.	A
Al ₂ O ₃ * vs. Tungsten Carbide*	Tilting Pad	S-S	Completed 1000 cycles at 4 psi.	A
		H.S.	Failed after 50 drops of 1 lb.	C
Al ₂ O ₃ * vs. Cold- Worked Haynes 25	Thrust Bearing	S-S	Completed 1000 cycles at 1.5 psi. Brg. distorted, did not complete test	B
		H.S.		B
Al ₂ O ₃ * vs. Cold- Worked Haynes 25	Tilting Pad	S-S	Failed after 180 cycles at 4 psi.	C
		H.S.	Failed after 2 drops of 3 lbs.	C
Al ₂ O ₃ * vs. Chrome carbide*	Thrust Bearing	S-S	Failed after 60 cycles at 1 psi.	C
		H.S.	Failed after 8 drops of 7 lbs.	C
Al ₂ O ₃ * vs. Chrome carbide*	Tilting Pad	S-S	Run at 1400 F, not at 900 F.	-
		H.S.	Did not fail after 20 drops of 3 lbs.	A
Al ₂ O ₃ * vs. Chrome carbide*	Thrust Bearing	S-S	Completed 1000+ cycles at 2.5 psi.	A
		H.S.	Completed test without failure.	A

TEST TEMPERATURE - 1400 F.

Al ₂ O ₃ * vs. Chrome Carbide*	Tilting Pad	S-S	Completed 1000 cycles at 4 psi.	A
		H.S.	Run at 900 F. instead of 1400 F.	-
Al ₂ O ₃ * vs. Stellite 6*	Thrust Bearing	S-S	Completed 1000 cycles at 1.4 psi.	A
		H.S.	Completed test without failure.	A
Al ₂ O ₃ * vs. Stellite 6*	Tilting Pad	S-S	Completed 1000 cycles at 4 psi.	B
		H.S.	Failed before reaching speed.	C
Rene 41 vs. BaF ₂ /CaF ₂ film	Thrust Bearing	S-S	Failed after 90 cycles at 1 psi.	C
		H.S.	Not run.	-
Ni-Cr alloy* on Rene 41 vs. BaF ₂ /CaF ₂ film	Tilting Pad	S-S	Completed 1000 cycles at 4 psi.	B
		H.S.	Failed before reaching speed.	B - C
Ni-Cr alloy* on Rene 41 vs. BaF ₂ /CaF ₂ film	Thrust Bearing	S-S	Failed after 590 cycles at 2 psi.	B
		H.S.	Failed after 12 drops of 1 lb.	C

(a) *Denotes coating applied to metallic substrate.

(b) S-S is start-stop, H.S. is high speed rub.

(c) A is good, B is fair, C is poor.

(d) See Pages 16 through 19 for the load-cycle sequence for each test.

1.0 INTRODUCTION

One of the major advantages of gas-lubricated bearings is their potential for long life over very wide temperature ranges, particularly for high speed turbo machinery. Up to the present time, very little has been done to exploit this potential. Most gas bearing machines are designed for relatively low temperature operation under conditions which are as close to isothermal as possible. Significant gains in design and turbine cycle efficiency could be realized if the machines could be operated at higher temperatures under non-isothermal conditions.

Bearing materials present a major barrier to high temperature operation. Thermal gradients, dimensional instability, creep, and growth due to centrifugal forces, will all combine to change the bearing clearances, often in unpredictable ways. This will increase the possibility of accidental rubbing contacts and seizure during high speed operation. In addition, if hydrodynamic bearings are to be used, the necessity for starts and stops over a wide operating temperature range will place additional burdens on the sliding compatibility of the materials. The fact that these bearings are supported on very thin films of gas means that surface damage and wear must be kept to a minimum.

Under contract NAS 3-4179, MTI had previously conducted two experimental programs to evaluate the sliding behavior of materials and coatings for use at temperatures of 350 F and 500 F in argon (1,2). The results of that work were also summarized in the open literature (3). For temperatures up to at least 500 F, self-bonded chrome oxide coatings on metallic substrates showed outstanding resistance to surface damage and wear.

The purpose of this current program, under contract NAS 3-9433, was to select and evaluate bearing material combinations suitable for use in the temperature range from 900 F to 1400 F. Major emphasis was placed on the resistance of these materials to sliding damage, but efforts were also made to assess other factors such as dimensional stability.

This was, in every sense of the word, an exploratory program. It started out to be a relatively straight-forward series of evaluations of the sliding behavior of materials which could be used for gas bearing applications at elevated temperatures. Yet, many practical problems and unknowns that have to be faced in building and running a full scale gas bearing machine at high temperature were encountered and had to be resolved during the experimental work. In hindsight, it seems difficult enough to build a gas bearing system to run at high speed and at glowing red heat without adding in the need to impact it repeatedly to see how much abuse it would take. However, this is precisely the type of investigation that has to be undertaken in order to insure that gas bearings are developed that will operate reliably in Brayton cycle machinery and that will be able to sustain substantial shock and off-design operating conditions, without resulting in a machine failure.

This program was divided into two phases. Phase I consisted of two tasks which involved analysis and design of high temperature bearings. Phase II, which is the subject of this report, was also broken down into the following two tasks:

Task III - Bearing Materials Screening Study

This task consisted of a study of the literature and related programs to identify potentially useful substrate materials, solid lubricant coatings and wear resistant surface coatings suitable for use in gas bearings operating in an inert gas atmosphere at temperatures from 900 F to 1400 F.

Task IV - Experimental Evaluation of Bearing Materials

In this task, six bearing material combinations, selected from the screening study were evaluated as hydrodynamic journal and thrust bearings in the temperature range from 900 F to 1400 F. Both start-stop and high speed rub tests were run in an argon environment.

This report summarizes the results of the work under Tasks III and IV.

2.0 APPROACH TO THE PROBLEM

To satisfy the requirements of this type of application, it was anticipated that the major problem areas, as far as materials were concerned, would be as follows:

1. Sliding compatibility between the bearing and the journal during starts and stops, or in the event of a high-speed rub.
2. A lack of useful information concerning the dimensional stability of materials at high temperature.
3. Adequate strength of materials at high temperature.

The results of the Phase III Bearing Material Screening Study on candidate materials are included as Appendix A of this report. In that section, the reasons for selecting particular combinations are given in some detail. However, the general philosophy of using coatings for surface protection against sliding damage, and the techniques which were used to evaluate these coatings, warrant additional emphasis at this point since this is really the focal point of this work.

2.1 The Use of Coatings

In the last few years, the importance of selecting gas bearing materials for good sliding behavior has been receiving some well-deserved attention. This is the result of several factors including the following:

- The transition of gas bearings from laboratory curiosities to practical support systems.
- The number of premature failures which were caused by damage to bearing surfaces during assembly or by momentary rubs due to unstable operation.
- The need for greater reliability in practical machinery.
- The realization that gas bearing machinery would have to be capable of withstanding shock and vibration in many applications.

- The trend toward self-acting hydrodynamic bearings.

Little has been published in the open literature on gas bearing material combinations. References (4 to 9) describe some material experience in this area but most of these were bearing design rather than bearing material evaluations, and the loads, lift-off speeds, number of starts and stops, etc. are not reported. Table I lists a number of materials which were known to have been used in the past in various applications in England, France, and in the U. S. With the exception of the DU, the carbon graphites and the solid lubricant films, none of these material combinations could survive a high speed rub and most of them had limited start-stop capability. The DU and the carbon-graphites were difficult to retain and made very unreliable gas bearing systems while the solid lubricant films had limited wear life and could only be applied effectively on steel or bronze surfaces. In addition, all of these materials were very restricted in temperature capability.

Solid ceramics or cermets have been used to solve this problem of sliding behavior, particularly in small, high precision gas bearings such as guidance gyroscopes, but the problems of fabricating and mounting these materials in large machines are formidable. These problems, coupled with the fact that the mechanical properties of these materials could impose unreasonable limitations on their use as high speed rotating components discourage their use in large bearings.

In the early stages of the MTI work on gas bearing machinery, it became apparent that some provision would have to be made to protect bearing surfaces from damage particularly during high speed rubs. The gas bearing machine has yet to be designed that can be built, assembled, and run through initial check-out without sustaining some rubbing contacts. To risk a machine by ignoring the possibility of surface damage during sliding contacts would be very foolhardy. Yet, it would be equally impractical to design a machine around materials which were mechanically unsuitable except for the fact that they had the ability to slide effectively. Coatings or surface treatments represented the best compromise. This would permit the

designer to select an alloy with adequate strength, corrosion resistance and dimensional stability for the shaft, bearings and any other critical structural members. Then, surface coatings could be used to achieve good sliding compatibility and any other surface properties which might be required. This approach minimizes many design problems such as matching parts for differential thermal expansion and the mounting or positioning of components. Its chief value lies in the fact that it gives the design engineer adequate leeway to choose the best available materials without having to make design compromises simply because of sliding behavior. In addition, the variety of coating materials which are available makes it possible to select the best materials for almost any environment.

The coating materials which have proved to be most successful to date fall into two general categories:

Low shear strength, solid lubricant films

Hard, wear-resistant coatings

The former category includes such films as resin or ceramic bonded MoS_2 and graphite as well as soft, complex eutectic coatings such as the NASA fluoride films.

The latter category of hard coatings covers both diffusion treatments such as nitriding, chromizing, etc., and also applied coatings such as electroplatings or plasma-sprayed coatings. (This distinction may be more apparent than real, because it is likely that all plasma coatings are also bonded to the substrate by diffusion mechanisms. However, this is a convenient way to classify these coatings.)

Experience with diffusion treatments, particularly nitriding, has been very unfavorable. These surfaces have very poor sliding compatibility as compared to the plasma-sprayed coatings such as the oxides or cermets. Another major advantage of plasma-sprayed coatings is the fact that they can be applied to almost any type of metallic substrate.

For the reasons cited above, MTI has concentrated its efforts on the use of plasma coatings in all gas bearing machinery and the major effort in this program was directed toward finding coating compositions which could be used at high temperature.

2.2 Evaluation Test Techniques

In conjunction with this work on the selection of coatings, special test techniques have also been developed to evaluate these coatings under realistic bearing conditions. In the past, the selection of gas-bearing material combinations has been made using test data from conventional friction and wear bench tests. While these tests have been found to be useful for screening candidates, experience has shown that they do not truly simulate the problems encountered in a gas bearing. Some materials have given excellent results, even at high sliding velocity, in bench test machines. However, when these same materials were used in an actual gas bearing, catastrophic failures took place during high-speed runs.

The reason for this behavior is understandable. First of all, in a gas bearing the effect of wear or the surface damage on hydrodynamic bearing operation is the primary consideration. This is not predictable in any way from simple sliding tests. Secondly, the sliding conditions are different in gas-lubricated bearings where the sliding time in contact is short and there are definite limiting clearances. In continuous sliding, there may be some initial surface damage which is obliterated in time. From bench tests, such materials may appear satisfactory, while in a bearing test, failure can result. The clearance and the geometry of the bearing will ultimately determine the amount and type of damage or loose debris which may be tolerated without seizure.

As a result of this experience, a gas-bearing test has been developed to evaluate promising materials under realistic bearing conditions. For tilting-pad journal bearing studies, the test consists of a single, self-acting tilting-pad which is dead-weight loaded against the journal. Thrust bearing evaluations are made by using a self-acting thrust bearing

with a Whipple groove pattern, running against a dead-weight loaded, flat thrust collar. Both start-stop and high speed rub tests are made to evaluate the durability of the bearings. Specialized instrumentation is used to measure the important variables in these tests. Essentially, this equipment measures the effect of sliding on the subsequent hydrodynamic bearing performance.

In the section on Test Equipment, the test rig is described in greater detail.

2.3 Previous Experience on Coatings

As noted in the Introduction, under an earlier NASA contract, MTI had investigated the feasibility of using coatings to protect the surface of bearings operating at temperatures from 350 F to 500 F (1-3). In those studies, the following combinations were evaluated:

Bearing Surface	Journal Surface	Test Temp.	Environment	Stress
Resin bonded MoS ₂ solid lubricant film (a)	Hardened Steel	75 F 300 F	Air Argon	4 psi
Plasma sprayed chrome oxide (b)	Same as bearing	75 F 300 F 500 F	Air and Nitrogen Argon Argon	4 psi
Flame plated nickel bonded tungsten carbide (b)	Flame plated Al ₂ O ₃ (b)	75 F 300 F	Air Argon	4 psi
DU (c)	Plasma sprayed molybdenum (b)	300 F	Argon	2.4 psi
hardened M-50 tool steel	Flame plated cobalt bonded tungsten carbide (b)	500 F	Argon	4 psi

- (a) This coating was lapped down to a thickness of 0.0001-0.0002 inches before testing.
- (b) These were coatings, 0.003 inches thick, on metal substrates
- (c) A proprietary composition made by Glacier Metals Ltd. Consists of spherical particles of bronze sintered to a thin steel backing. Porous bronze surface then impregnated with Teflon and lead.

In the start-stop tests, the materials ranked in order of decreasing effectiveness as follows:

<u>Bearing Surface</u>	<u>Journal Surface</u>
1. Plasma-sprayed chrome oxide	Same as bearing
2. Flame plated nickel-bonded tungsten carbide	Flame plated Al_2O_3
3. Resin bonded MoS_2 film	Hardened steel
4. DU*	Molybdenum coating
5. Hardened M-50 steel	Flame plated tungsten carbide

* Run at stress of 2.4 psi instead of 4 psi.

In the high speed tests, only the self-mated chrome oxide and the DU showed real promise. The chrome oxide coating was able to survive over a hundred high speed rubs at various shock loads without any apparent damage. The contact areas were smooth and highly polished as shown in Fig. 1. For contrast, Fig. 2 shows the severe abrasion which occurred with the tungsten carbide coated pad running against the Al_2O_3 coated journal. The DU material was very effective during the high speed rubs, but gave very poor results in the start-stop tests. This, coupled with the fact that the material was difficult to fabricate and retain, makes it a poor choice for gas bearing usage.

The resin bonded MoS_2 film was effective as long as the film remained intact but, in both the start-stop tests and the high speed rub tests, metal transfer and scoring was noted before the end of the run. It was felt that the use of a solid lubricant film applied over one of the plasma-sprayed coatings would be a better approach. This would reduce the friction considerably and thus minimize the amount of heat generated during a high speed rub. It would also reduce starting torque problems in hydrodynamic bearing systems. Figure 3 shows a bearing pad was coated with chrome oxide plus a resin bonded MoS_2 film on top of the chrome oxide. This pad was subjected to 100 high speed rubs at 48,000 rpm in air at room temperature. The original grinding marks are still visible and there does not appear to have been any wear. Even if the MoS_2 coating had been worn away, the chrome oxide coating would still have been effective in preventing surface damage.

It is important to note that subsequent experience in full scale gas bearing machinery has demonstrated that essentially the same results are obtained with complete bearing systems as are obtained on the single pad bearing tests. For example, under Navy contract (10), MTI has been evaluating the effect of shock loads on gas bearing performance. The test rig consists of a 2.375 inch diameter motor-driven shaft, weighing 65 pounds, which is mounted on two tilting pad journal bearings and two thrust bearings. The shaft is brought up to a speed of 8,000 rpm, and impact loads are applied to the base of the machine by means of a pendulum hammer. Accelerometers, mounted on the machine casing, sense the g-levels to which the machine is subjected. Capacitance probes are used to monitor the performance of the bearings.

Gas lubricated journal and thrust bearings, coated with chrome oxide, have been subjected to 1400 impacts of 40 g's on the casing without destroying the bearings. Both hydrostatic and hydrodynamic bearings were evaluated. A photograph of one set of the hydrodynamic bearing pads and journals is shown as Fig. 4. Talysurf traces of the wear areas show only slight change in surface finish although the bearings are definitely worn. The hydrostatic bearings were in even better condition.

Chrome oxide coatings have also been used in a number of MTI gas bearing machines, including the gas-lubricated axial flow turbocompressor simulator which was built by MTI under subcontract to Pratt & Whitney Aircraft for the NASA Lewis Research Center (11) and for the water-lubricated bearings of the circulator being built by General Atomic for the Colorado Gas and Electric Company.

2.4 Candidate Materials for High Temperature Bearing Coatings

Chrome oxide is very strictly limited to use below 1000 F because of thermal spalling. At temperatures just over 1000 F, the coating begins to show spalling at the edges of the bearing. At 1200 F and above, the coating becomes loose and powdery, indicating that the particle to particle bond is also being destroyed.

Under Air Force Contract (12), MTI recently concluded a study of coating materials for use in air at temperatures up to at least 1600 F. Based on the results, the following materials showed promise:

Self bonded Al_2O_3

Stellite 6

Nickel chrome-bonded chrome carbide

Since the NASA work was concerned with an inert gas environment, this opened up the possibility that other materials which had good sliding characteristics but poor oxidation resistance such as tungsten carbide, could also be included in this list.

The results of the initial work on the single, tilting pad bearing had shown that many of the hard-coated materials were able to survive the thousand start-stop tests with little or no measurable surface damage. However, in the high speed rub tests, it was found that any bearing material which was metallic or contained a metallic binder (such as the nickel-bonded tungsten carbide) would transfer metal to the journal surface. This transferred metal then caused scoring or welding.

The results were not too surprising since the sliding velocities and loads were very high. For example, at 60,000 rpm, with a 1.5 inch diameter shaft, the sliding velocity was about 390 feet per second. The impact loads were as high as 50-100 g's. Sufficient heat could be generated, even in a fraction of a second, to bring the surfaces up to the melting point of the metal. If the ambient temperature was also high, this problem would become even more critical. For this reason, it was hypothesized that the ideal coating material should not contain any metallic constituent. Self-bonded oxides, silicides, borides, carbides, or nitrides seemed to offer the most promise. In addition, attempts were made to establish other criteria which could be used to define the ideal coating combination. These included such variables as hardness, density, crystal structure, particle size, etc. To date, none of these has been found to be sufficient to be used as a criterion in defining the ideal coating. It has been established that the coating material

must wear in the form of fine, discrete particles rather than fracture and produce large agglomerates, but the conditions which control the wear process and particle size are not well defined. Density is known to affect the wear characteristics of the coatings, and it has been found that very dense coatings are not as effective as coatings with some degree of porosity. The porosity could be part of the key to controlling the size of the wear particles. In addition, the pores in the surface can trap particles and minimize the amount of loose material in the bearing clearance. Figure 5 shows the results of high speed rub tests on chrome oxide coatings of different densities. The high density coating shows considerable abrasion, while the lower density coating is smooth and polished in the contact area.

At this point, more thought was given to the hypothesis that self-bonded ceramic coatings were the most likely materials to resist high speed rubs. If two different coatings were being used on the journal and bearing surfaces, one a self bonded ceramic and the other a metal bonded carbide or oxide, it was anticipated that the relative positions of the coatings could have a significant influence on the sliding behavior. The reasoning behind this was as follows:

If the bearing pad is impacted against the journal, the contact area on the journal is continuously changing as the shaft is rotating. However, the contact area on the pad is essentially fixed. This means that thermally induced sliding effects can be appreciably different depending on whether the metallic constituent is on the bearing and the non-metallic coating is on the journal, or vice versa.

The heat generated by friction, $Q = \frac{fLV}{J}$ where

f	=	friction
L	=	load
V	=	velocity
J	=	mechanical equivalent of heat

The surface temperature depends on the way that this heat is dissipated from the surface. If the geometries are identical, then the surface temperature $T \propto \frac{fLV}{2AK}$
 where A = area
 K = thermal conductivity

For the case of a practical bearing system, where a fixed area on the bearing is continually in contact with a moving contact area on the journal, the problem

becomes much more complex, particularly for the case where two different coatings, with markedly different thermal conductivities and diffusivities, are being used. It is difficult to predict how the surface temperature will affect the sliding behavior. In some cases, high contact temperatures might result in heavy material welding and transfer, in others, it might simply reduce the shear strength of the surface asperities and give lower friction.

One of the goals of the bearing tests was to evaluate this effect experimentally.

3.0 TEST EQUIPMENT AND TEST PROCEDURE

3.1 Test Rig

A layout drawing of the test rig is shown in Fig. 6 as MTI Drawing No. 186J01. In the following verbal description, the numbers in parentheses refer to the part numbers shown on the layout drawing.

Essentially, this rig consisted of a support shaft (1) mounted on two high speed, preloaded, angular contact bearings (2). A Rene 41 heat dam (3) was shrunk on one end of the support shaft outboard of the ball bearing mounts. The actual test shaft (4) was then shrunk on the other end of the Rene 41 end cap (5) and the whole assembly was pulled together with a Rene 41 tie bolt (6) which was threaded into the support shaft (1). Only the overhung test shaft (4) and the Rene 41 heat dam (3) were in the hot zone. Heat baffles (7) were used to interrupt the flow of heat out of this area. The entire support shaft and ball bearing system was enclosed in a water-cooled housing (8). Lubrication for the ball bearings was provided by an air-oil mist. This air-oil mist was supplied through point (10) on the drawing.

Double labyrinth seals (9) blocked the air-oil mist from traveling down the test shaft and into the test chamber. In addition, pressurized argon gas was supplied between the double labyrinth seals through point (11) at a higher pressure than the air-oil mist, thus creating an additional barrier to oil leakage into the hot zone.

The tilting pad test bearing (12) was dead weight-loaded down against the test shaft (4). A Stellite ball pivot (13) on the back of the tilting pad bearing provided for self-alignment of the bearing. Load was applied by means of dead weights mounted on top of a vertical load arm (14). This arm was supported in a plain guide bushing (15).

Figure 7 is a photograph of the test rig as set up for the tilting pad bearing tests, except for the enclosure which was used for the argon blanketing. For the thrust bearing test, the rear rig was tilted 90° so the bearing could be run in the vertical position. In that orientation, the runner (16) was dead weight-loaded down against the thrust bearing stator (17). The thrust bearing was mounted on a Stellite ball pivot in the center of the back face to make the bearing self-aligning. A photograph of the test rig, set up for the thrust bearing tests, is shown in Fig. 8.

The shaft was driven by two systems, depending on the test. For start-stop tests, a 3400 rpm electric motor was attached directly to the cold end of the support shaft with a flexible coupling. For the high speed test, a compressed air-driven turbine (18) mounted in a nozzle box on the cold end of the support shaft, provided the drive.

Heat was obtained in the test area by means of the clam shell type furnace with quartz infrared heating tubes.

The test end of the rig, including the furnace, was enclosed in a case (19) with removable sides. By sealing all joints with silicone gaskets and bolting the sides in place, this case could be made reasonably leak-tight. The environment within this enclosure was controlled by maintaining a positive pressure of preheated argon gas into the case. All electrical, gas and water connections were made with feedthrough fittings mounted in the base of the test rig. Fig. 9 is a photograph of the test rig with the casing in place.

3.2 Instrumentation

One of the basic goals of these tests was to evaluate the hydrodynamic performance of the test bearing as a function of sliding contacts. To accomplish this goal, it was necessary to monitor the dynamic film thicknesses in order to see if the performance was deteriorating because of surface damage or wear.

In previous tests, the film thickness was measured by means of two capacitance type probes mounted on each side of the tilting pad bearing. These probes sensed the surface of the shaft, thus providing a direct measurement of the amount of lift-off. However, those tests were only run at temperatures up to 500 F. In these tests at 900 F and 1400 F, the state of the art of capacitance probe development was much less advanced. Probes were available for this temperature range, but they were considerably more bulky and less rugged than the low temperature probes. For this reason, probes were used to look at the back of the test bearing and at the test shaft. The film thickness, in this case, was the reading of the probes on the back of the bearing corrected for the shaft position, as indicated by the probes sensing the shaft. During the tests, the probe signals were fed into Wayne-Kerr proximity meters and displaced visually on an oscilloscope screen.

Since the capacitance probes were several inches long, and fixed to the top of the test chamber, relatively small changes in the temperature of the chamber caused the zero line to shift up and down. For this reason, it was necessary to read out the probe signals on an individual basis, i.e. each time a reading was taken, the probe signals were marked while the shaft was rotating. As soon as the shaft had come to a standstill, the position of the probe signals at that point was taken as zero line.

A magnetic speed pickup (20) mounted at the cold end of the support shaft (1) was used to measure shaft speed. This pickup produced six pulses for each revolution of the shaft. The signal from the pickup was fed into a Hewlett-Packard frequency meter for visual observation. The accuracy of the shaft speed readings was on the order of $\pm 2\%$.

A chromel-alumel sheathed thermocouple (22), located about 1/8" from the end of the test shaft was used to measure the ambient gas temperature in the test zone. A second thermocouple was also used to sense the same general area temperature. The actual temperature of the test bearings was measured with a chromel-aluminum thermocouple fastened directly to the back of the bearing. The bearing temperature generally held within ± 30 F in the 900 F tests, and within ± 60 F in the 1400 F tests.

In order to maintain an inert environment in the bearing test chamber, a low flow of argon gas was bled continuously into the chamber so as to maintain a slight positive pressure. The ambient pressure in the chamber was measured with a pressure tap (23) connected to a manometer. A positive pressure of about 1 or 2 inches of water was maintained while the equipment was being heated or cooled and during the start-stop tests. When the high speed tests were in progress, the argon pressure was appreciably higher because more argon gas was being supplied to the labyrinth seal area.

4.0 TEST PROCEDURE

4.1 Start-Stop Low Speed Sliding Tests

The purpose of these tests was to simulate bearing to shaft contact during low speed start and coastdown conditions without the introduction of hydrostatic lift-off. These tests were designed to evaluate the effect of low speed sliding contacts, under design loads, on the hydrodynamic performance of the bearings.

Test Requirements

- A. Number of material combinations - 6
- B. Temperature levels - 900 F and 1400 F
- C. Test specimen configurations.

The journal bearing configuration was a single shoe and mating journal. The thrust bearing configuration was a full thrust plate, with grooving and exposed edges against the mating thrust collar.

- D. Ambient conditions - Argon gas

The following procedure was used in each of the start-stop tests:

1. A Talysurf trace was made of the surfaces of the pad and shaft to establish the initial profile.
2. The test specimens were cleaned in an ultrasonic cleaner and mounted in the test rig.
3. The breakaway torque was measured at room temperature, in air, with a 4 psi stress on the bearing.
4. The test rig was heated to the test temperature with preheated argon gas flowing into the chamber and the breakaway torque was remeasured under load.
5. The start-stop cycle test was made.

6. At the end of the test, the torque was remeasured at the test temperature and again in air after cooling.
7. The shaft and pad surfaces were examined, photographed, and the surface profiles were remeasured.

Each combination was to be run for 1000 starts and stops, or until failure occurred, under a stress of 4 psi, based on the projected area of the bearing (LxD). The width of the tilting pad test bearing was 0.75 inches and the diameter of the journal was 1.5 inches. Thus, the projected area was 1.125 square inches and the load, divided by this area, was the average stress in pounds per square inch. The true stress was actually much higher since contact did not take place over the entire bearing area. In the case of the thrust bearing, the area was simply the overall bearing surface area.

A program timer was used to turn on the electric motor drive, bring the shaft up to a speed of 3400 rpm for five seconds, then shut the motor off and permit the shaft to coast to a complete stop.

The test data included:

1. Periodic monitoring of the dynamic film thickness to determine if any significant change was taking place in bearing performance.
2. Periodic monitoring of the capacitance probe readings under static conditions to determine if wear or surface damage had occurred.

4.2 High Speed Rubs Under Shock Loads

The purpose of these tests was to determine the ability of a hydrodynamic bearing to function properly after the bearing has been subjected to a predetermined number of high speed rubs.

Test Requirements

- a. Number of material combinations - 6
- b. Temperature levels - 900 F and 1400 F

c. Test specimen configurations.

The journal bearing configuration was a single shoe and mating journal. The thrust bearing configuration was a full thrust plate, with grooving and exposed edges against the mating thrust collar.

d. Ambient conditions - argon gas.

To apply the shock loads, a pivoted arm with adjustable weights was mounted on top of the case of the test rig. This arm was dropped from a height of one inch (controlled by a mechanical stop) to impact the top of the vertical load arm. This drove the bearing down against the shaft and caused a momentary rub. The definition and sequence of shock loads on the shoe and thrust bearing, respectively, was as follows:

<u>No. of Drops</u>	<u>Load-lb.</u>	<u>Drop Height</u>	<u>Remarks</u>
50	1	one inch	
20	3	one inch	Disassemble and examine
10	5	one inch	
10	7	one inch	Disassemble and examine

Shaft speed 38,500 rpm at rub impact.

During the course of this program, measurements were made to establish the magnitude of the forces which these impact loads represented. This was done when the test rig was mounted vertically for the thrust bearing tests. Two accelerometers were used. One of these accelerometers was mounted near the top of the vertical load arm, just below the point at which the pivoted hammer impacted the load arm. The second accelerometer was mounted on the turbine end of the ball bearing supported shaft. The shaft was not rotating, and the thrust bearing and the thrust collar were clamped together. The first (top) accelerometer was measuring the full impact, while the second (bottom) accelerometer was measuring the impact after it had been damped down by the load arm, the thrust bearing, the support shaft, and the ball bearings which held the support shaft. The signals from these two accelerometers were displayed simultaneously on an oscilloscope screen and were photographed for measurements. The following results were obtained:

<u>Impact</u>	<u>Top Accelerometer</u>	<u>Bottom Accelerometer</u>
1 pound from 1" height	185 g's	18 g's
3 pounds from 1" height	300 g's	54 g's
5 pounds from 1" height	600 g's	75 g's
7 pounds from 1" height	670 g's	75 g's

Previous measurements of the time in contact had shown that the bearing actually rubbed against the journal for about 0.02 to 0.05 seconds during each impact. This time was independent of the actual load.

Prior to each test, Talysurf traces of the bearing surfaces were made. The test specimens were then cleaned, the test was assembled and the rig was heated to temperature with a low flow of preheated argon gas bleeding into the chamber. The shaft was brought up to a stable operating speed with a load of about 1.5 psi on the bearings. (Some load is essential to prevent bearing flutter at high speed) and the shock tests were run. Bearing performance during the tests was monitored by observations of the change in the dynamic film thickness.

After the test, another set of Taylsurf traces and photographs were taken to show the appearance of the test surfaces.

5.0 TEST RESULTS

5.1 Start-Stop Tests

The following combinations were evaluated in the start-stop tests:

900 F. Tests

<u>Tilting Pad Bearing</u>	<u>Journal</u>
Chrome oxide coated 4340 steel	Chrome oxide coated 4340 steel
Al ₂ O ₃ Coated A-286 stainless stl.	Cobalt-bonded tungsten carbide coating on A-286 stainless
Al ₂ O ₃ Coated Haynes 25 (solution treated)	Cold-worked Haynes 25 (no coating)
<u>Grooved Thrust Bearing</u>	<u>Mating Thrust Collar</u>
Chrome oxide coated 4340 steel	Chrome oxide coated 4340 steel
Cobalt bonded tungsten carbide on A-286 stainless	Al ₂ O ₃ coated A-286 stainless
Al ₂ O ₃ coated Haynes 25 (solution-treated)	Cold-worked Haynes 25 (no coating)
Nickel chrome bonded chrome carbide on TZM molybdenum	Al ₂ O ₃ on TZM molybdenum

1400 F. Tests

<u>Tilting Pad Bearing</u>	<u>Journal</u>
Al ₂ O ₃ coated TZM alloy	Nickel chrome bonded chrome carbide on TZM alloy
Al ₂ O ₃ coated TD nickel	Stellite 6 coated Haynes 25 (solution-treated)
Rene 41 (no coating)	BaF ₂ /CaF ₂ film on Rene 41
<u>Grooved Thrust Bearing</u>	<u>Mating Thrust Collar</u>
Nickel chrome bonded chrome carbide on Rene 41	Al ₂ O ₃ coated Haynes 25 (solution-treated).
Nickel Chrome alloy on Rene 41	BaF ₂ /CaF ₂ film on Rene 41
Stellite coating on Haynes 25 (solution-treated)	Al ₂ O ₃ coating on TD nickel

5.1.1 900 F. Tilting Pad Journal Bearing - Start Stop Tests

Chrome Oxide Pad vs. Chrome Oxide Coated Journal

This combination ran very effectively for 1000 starts and stops. There was a gradual decrease in the running film thickness during the test. Initially, the bearing was running on a film about 0.8 mils thick and, at the end of the test, the film was about 0.5 mils. After the test, it was observed that both the pad and journal surfaces were polished smoothly in the contact areas. It was noted that very slight chipping had occurred at the edges of the pad in the loaded zone. Since 900 F is very close to the maximum temperature at which chrome oxide can be used, it may be that the combination of load and temperature was enough to cause this damage. The edges are always the weakest areas on the coated bearings. As shown in Table 3, there was no significant change in the surface roughness of the pad bearing. The journal surface finish had improved slightly. Photographs of these surfaces are shown in Fig. 10.

Al₂O₃ Coated Pad vs. Tungsten Carbide Coated Journal

As was the case with the chrome oxide, this combination survived the 1000 starts and stops with no difficulty. There was a small decrease in running film thickness during the test. When the surfaces were examined, the carbide-coated journal surface showed only faint contact marks. The Al₂O₃ coated bearing pad had streaks of transferred material which were smooth and polished. According to the Talysurf trace, the only damage on the pad was an isolated scratch about 75 micro-inches deep.

Photographs of the specimens are shown in Fig. 11.

Al₂O₃ Coated Pad vs. Uncoated, Cold-Worked Haynes 25 Journal

After 180 starts and stops, this combination was not able to run as a self-acting bearing. It was found that considerable material had been transferred from the journal to the pad, mainly at the edges of the pad, and that this transferred material was causing the contact through the

film. As shown in Table 3, the material buildup on both edges of the pad was of the same dimensions as the film thickness. Photographs of the surface damage are shown in Fig. 12

This failure was somewhat surprising. In a previous study (12), it had been found that Al_2O_3 running against a Stellite coating in air at 1400 F was a reasonably good combination. The explanation for this discrepancy may be due to the fact that the previous test was run in air and that an oxide film of appreciable thickness had formed on the Stellite coated journal. Since the current tests are being run in argon, no protective oxide films would be present on the surfaces.

5.1.2 1400 F. Tilting Pad Journal Bearing - Start Stop Tests

Al_2O_3 Coated Pad vs. Stellite Coated Journal

This combination survived the 1000 starts and stops, but it was very noisy during coastdown and, after about 700 starts and stops, the probes indicated isolated touches while the journal was rotating at 3400 rpm. After the test, it was observed that material had transferred from the Stellite-coated journal to the Al_2O_3 coated bearing. This transfer was in the form of small isolated islands of material. Apparently, the sliding action had polished down this transferred metal because the Al_2O_3 surface was relatively smooth. As shown in Table 5, the journal surface had deteriorated as the result of the sliding contacts. Photographs of the surfaces are shown in Fig. 13.

Al_2O_3 Coated Pad vs. Nickel-Chrome Bonded Chrome Coated Journal

Excellent performance was obtained with this combination during the 1000 start-stop cycles. As shown in Fig. 14, both surfaces were in good condition after the test.

It is interesting to note that the Al_2O_3 coating, which was on a TZM molybdenum substrate, had changed color from white to a dark, dull gray. At this time, there is no adequate explanation for this color

change. It was not caused by material transfer, both the journal and pad surfaces were highly polished where contact had taken place and the Al_2O_3 surface was dark, even in areas which were not in contact with the journal. Neither the appearance of the surface nor the torque measurements indicated that this change was due to organic contamination. It is possible that enough oxygen was present in the coating to form a lower oxide of molybdenum on the substrate (MoO_2 and Mo_2O_3 are black) and that this oxide was reacting with the Al_2O_3 or diffusing through the coating.

Uncoated Rene 41 Pad vs. $\text{CaF}_2/\text{BaF}_2$ Eutectic Coated Journal

Some unexpected problems were encountered with this solid lubricant film. When the test rig was heated to 1400 F., and the test was started, the bearing would not lift at all for the first ten cycles. After that, the performance gradually improved and the bearing was running effectively after about fifty cycles. During the test, it was observed that the fluoride film was migrating up the sides of the pad and that some vapor was condensing on the probes which were sensing the back of the pad. This condensed material formed a green coating which finally shorted out one of the probes before the test was concluded.

In spite of these problems, the fluoride film did provide good protection for the surfaces and the bearing completed the 1000 start-stop cycles. When the surfaces were examined after the test, it was found that an appreciable amount of the fluoride film had transferred from the journal to the uncoated pad, especially in the loaded zone. This transfer can be seen in Fig. 15. No surface damage was observed on the Rene 41 specimens. In one area around the center of the journal, most of the film seemed to have been removed from the surface of the journal.

5.1.3. 900 F. Thrust Bearing - Start Stop Tests

From the outset of the thrust bearing tests, it was obvious that these bearings would be a more serious problem than the tilting pad journal

bearings. In the journal bearing, as long as the clearances were held within a certain range, the load carrying capacity was essentially constant. Since the actual area of contact in the journal bearing was limited primarily to the loaded zone, and since debris could escape readily from the contact area, this tended to mask the effect of minor surface damage and wear particles. In the thrust bearing, there was very little in the way of forgiveness. When the surfaces were flat, clean, and running true, there was no problem. However, crowning or dishing, or loose particles trapped in the clearance, did have a drastic effect on load-carrying capacity.

Preliminary experience in these tests showed that the bearings would carry a stress of 4 psi when they were first set up in the rig, and the load applied while the bearing was running. This load was being carried on very thin gas films, on the order of 100 to 200 micro-inches thick. After even a very small number of starts and stops, the load carrying capacity of the bearing deteriorated rapidly, due to slight amounts of surface damage or wear debris in the contact area. This made it necessary to reduce the load so that the bearing would be operating on a thicker film.

The most severe rubbing condition existed on the outer edge of the bearing. This was especially noticeable during coastdown because the rotor decelerated quite slowly. As the bearing slowed down, the initial contact took place on one edge. The resulting friction then tilted the bearing (it was pivoted on a single ball mounted on the center of the back of the bearing) and caused a rub on the opposite edge. This tilting action continued until the film became so thin that the center of the bearing surfaces began to share the load. The motion was extremely rapid and resembled stick-slip. Actually, this is the same condition which would be encountered in any flexibly-mounted thrust bearing.

In order to get any kind of reasonable data on these materials, it was necessary to modify the test procedure as follows:

1. The test rig was heated to the desired test temperature.
2. The bearing was rotated at motor speed, 3400 rpm.
3. Load was applied to the rotating bearing until the running film thickness had decreased to about 0.3 mils.
4. The test rig was stopped and then restarted under load.

If the bearing appeared to be able to operate with this load, then the start-stop tests were initiated. Generally, the bearing performance deteriorated during the test and it was necessary to reduce the load periodically whenever the bearing failed to lift-off completely.

From a practical standpoint, the fact that the tests could not be run at a stress of 4 psi was not completely unexpected. Past experience has shown that self-acting thrust bearings generally get into trouble at stress levels above 2.5 psi and this is normally considered to be the upper limit in the design of these bearings.

The results of the start-stop tests on the thrust bearings are summarized in Tables 6 and 7 and are described in the following paragraphs.

900 F. Thrust Bearing Start-Stop Tests

Chrome Oxide on 4340 Steel vs. Chrome Oxide on 4340 Steel

The test was started with a stress of 2.4 psi on the bearing. With this load, the running film thickness was about 400 micro-inches. After 10 start-stop cycles, the stress had to be reduced to 2 psi because of asperity contacts through the gas film. After a total of 75 cycles, the stress had to be reduced to 1.5 psi and, after 420 cycles, the stress was cut to 1 psi. At the end of 615 starts and stops, the test was terminated because the bearing was not completely lifted, even at this stress level. These results are summarized in Table 6.

A photograph of the surfaces of the thrust bearing and thrust collar is shown in Fig. 16. Most of the damage was in the form of abrasive wear, but there was one small chipped area on the edge of the thrust collar.

A sketch of the topography of the bearing after the test is also included in Fig. 16. The loss in load carrying capacity was apparently due to high wear on the outer edges of the lands.

The results of this first test raised a question regarding the design of the thrust bearing grooves. This chrome oxide coated bearing had an initial groove depth of about 1.5 mils, which was a reasonable depth for a high speed thrust bearing. However, for operation at 3400 rpm, this was far too deep a groove for optimum performance.

This presented at least three alternate choices: first, run the remainder of the thrust bearing tests with the same 1.5 mil groove depth as was used for the chrome oxide; second, use the same 1.5 mil groove depth and increase the running speed to generate thicker gas films; third, decrease the groove depth to 0.7 mils to achieve a more optimum geometry for use at 3400 rpm.

The former choice, of continuing to test at 3400 rpm with the 1.5 mil groove depth, was unrealistic since the actual machinery would not be run for any length of time under conditions where complete liftoff was not achieved. The second choice, of running at higher steady state speeds, was a reasonable solution, but would have meant changes in the set-up of the test rig and in the test procedure. The third choice seemed to be the most desirable since it preserved all of the standard operating conditions. All that was necessary was to decrease the groove depth for better low speed performance. For the remainder of these start-stop tests, groove depths on the order of 0.7 mils were used.

Tungsten Carbide (Grooved) on A-286 vs. Al_2O_3 on A-286

This test was started with a stress of 3.2 psi on the bearing. After 30 start-stop cycles, the stress had to be reduced to 2 psi and, after 120 cycles, to 1.5 psi. The bearing completed 1000 start-stop cycles at the 1.5 psi stress level.

Photographs of the surfaces and of the gross surface topography are shown in Fig. 17. Some material transfer from the carbide to the Al_2O_3

was observed. The thrust bearing lands were slightly worn at the outer diameter, thus giving the bearing a slight crown. The surfaces were in good condition. To bring the load carrying capacity of this bearing back to its original level, it would only be necessary to relap the surfaces lightly.

Uncoated Haynes 25 Cold-Worked vs. Al_2O_3 (Grooved) on Haynes 25

As was the case in the journal bearing tests, this combination gave very poor results. The bearing was apparently damaged almost immediately. An attempt was made to run at a stress of 1 psi, but the bearing would not lift after 60 start-stop cycles.

Photographs of the surfaces are shown in Fig.18. Metal had transferred from the Haynes 25 to the Al_2O_3 surface. The Al_2O_3 lands were badly worn and both surfaces showed considerable abrasion damage.

Chrome Carbide (Grooved) on TZM vs. Al_2O_3 on TZM

The original plan had been to run this combination at 1400 F. However, since the test results indicated that there were very few promising combinations capable of surviving these tests, even at 900 F, it seemed advisable to establish whether the Al_2O_3 vs. chrome carbide would be capable of satisfactory performance at 900 F.

The test was started with a stress of 3.3 psi on the bearing. After 30 start-stop cycles, the bearing seemed to have trouble in lifting off, so the stress was reduced to 2.4 psi. After about 20 more cycles, the bearing would not lift at all. It was found that the load arm was slightly bent and this was preventing the pivot from aligning the bearing. The bearings were still in fairly good condition and, after relapping the surfaces lightly and replacing the load arm, the same bearings were put back on test.

This time, a 2.5 psi stress level was used. The bearing completed 1000 starts and stops with no difficulty. Since the bearing appeared to be running better

at the end of the test than it was in the beginning, the stress was increased to 3.2 psi and 270 more start-stop cycles were accumulated.

Photographs of the surfaces are shown in Fig. 19. A small amount of material transfer was noted, but the surfaces appeared to be in good condition. For some unknown reason, the bottoms of the grooves on the chrome carbide coated bearing show sliding patterns, even though no contact could occur in these areas.

5.1.4 1400 F Thrust Bearing - Start-Stop Tests

Chrome Carbide (Grooved) on Rene 41 vs Al_2O_3 on Haynes 25

In view of the fact that the chrome carbide Al_2O_3 combination gave the best results at 900 F, a new test was set up to evaluate these coatings at 1400 F. Originally, one extra TZM thrust bearing had been made for these tests. This bearing had been sent to an outside vendor for coating a groove pattern through a mask. The results were unsatisfactory and, in attempting to strip the coating by chemical means, the vendor dissolved the TZM substrate. Since no other TZM specimens were available, the chrome carbide was applied to a Rene 41 substrate and the Al_2O_3 was coated on a Haynes 25 solution treated thrust collar.

An attempt was also made to coat both the Al_2O_3 and the chrome carbide surfaces with a solid lubricant film, Dow Corning X-15. This is a ceramic bonded MoS_2 coating which had shown promise in previous high temperature sliding tests. However, most of the solid lubricant coating was removed in the process of lapping the surfaces to the required flatness, and it is very doubtful if enough coating was left to have any significant effect on the results.

The test was started with a stress of 3.2 psi on the bearing. After about 50 start-stop cycles, the stress had to be reduced to 2.5 psi. Even at this load, the bearing was operating on a very thin film, less than 100 micro-inches. After 225 more cycles, the stress had to be reduced to 1.4 psi. The bearing completed the 1000 starts and stops at

this stress level. Photographs of the surfaces are shown in Fig. 20. The streaked appearance of the bottoms of the grooves is the result of the solid lubricant coating which had run into the groove area during the application process. No good measurements could be obtained on the wear pattern of the grooved thrust bearing because of the uneven nature of the solid lubricant coating on the bottom of the grooves.

Stellite 6 on Hayres (Grooved) vs. Al_2O_3 on TD Nickel

This combination was behaving poorly from the start. An attempt was made to run at 2 psi, but after 10 cycles the load had to be reduced to a stress level of 1 psi. After a total of 90 cycles, the bearing would not lift, even at this low load. Photographs of the surfaces are shown in Fig. 21. Some heat checking is apparent on the Al_2O_3 surface and, to a lesser extent, on the Stellite. The grooves were almost completely obliterated at the edge.

This was not a particularly impressive combination in the journal bearing tests, although it did complete 1000 start-stop cycles. These results emphasize the fact that the thrust bearing tests are a much more severe evaluation of material performance.

Nickel-Chrome Alloy on Rene 41 (Grooved) vs. Fluoride Coating on Rene 41

In order to run this test, it was necessary to put a groove pattern on the Rene 41 thrust bearing. Since it was difficult to photoetch the grooves in this alloy, a nickel-chrome alloy was sprayed on the Rene 41 surface through a mask to form the groove pattern.

This bearing combination behaved the same way as in the journal bearing test, i.e., the bearing would not lift, even at light load, until it had been run for several start-stop cycles. After 45 cycles at a stress level of 1.4 psi, the bearing appeared to be lifting properly. The stress level was then increased to 2 psi. At the end of 590 cycles the bearing was definitely touching at speed. The test was shut down at this point.

Figure 22 shows the appearance of the surfaces. There was considerable transfer of the fluoride film from the thrust collar to the grooved thrust bearing. The nickel-chrome lands showed slight wear on the outer edge, which could account for the gradual loss in load carrying capacity. Possibly, this combination might have been more effective if the grooves had been photoetched in the Rene 41, but this appeared to be too much of a development study.

No unusual problems were encountered with the fluoride film in this test, although there was still some migration of the film on the sides of the thrust runner. If any material did vaporize, it did not collect on the probes.

5.2 High Speed Rub Tests

The following combination were evaluated in the high speed rub tests:

900 F. Tests

<u>Tilting Pad Bearing</u>	<u>Journal</u>
Chrome oxide coated 4340 steel	Chrome oxide coated 4340 steel
Al ₂ O ₃ coated A-286 stainless	Cobalt bonded tungsten carbide coating on A-286 stainless
Al ₂ O ₃ coated Haynes 25 (solution treated)	Cold-worked Haynes 25 (no coating)
Al ₂ O ₃ coated Rene 41	Ni-Cr bonded Chrome Carbide on Rene 41
<u>Grooved Thrust Bearing</u>	<u>Mating Thrust Collar</u>
Chrome oxide coated 4340 steel	Chrome oxide coated 4340 steel
Cobalt-bonded tungsten carbide on A-286 stainless	Al ₂ O ₃ on A-286 stainless
Al ₂ O ₃ coated Haynes 25 (solution treated)	Cold-worked Haynes 25 (no coating)
Ni-Cr bonded Chrome carbide on TZM	Al ₂ O ₃ on TZM

1400 F. Tests

<u>Tilting Pad Bearing</u>	<u>Journal</u>
Al ₂ O ₃ coated TD nickel	Stellite 6 coated Haynes 25 (solution treated)
Rene 41 (no coating)	BaF ₂ /CaF ₂ film on Rene 41
<u>Grooved Thrust Bearing</u>	<u>Mating Thrust Collar</u>
Ni-Cr bonded Chrome Carbide on TZM	Al ₂ O ₃ coated TZM
Rene 41 with Ni-Cr alloy groove pattern	BaF ₂ /CaF ₂ film on Rene 41

These tests were run at a speed of 38,500 rpm. The test procedure was as follows.

- Talysurf traces of the bearing surfaces were made.
- The test specimens were cleaned and assembled in the test rig.
- The test rig was heated to temperature with a low flow of argon gas bleeding into the chamber.
- The shaft was brought up to a stable operating speed of 38,500 rpm with a preload of 1.5 psi on the bearing.
- A series of shock loads were applied to the bearing to cause high speed rubs. Performance of the bearing was monitored to determine the effect of these rubbing contacts on hydrodynamic performance.

The definition and sequence of shock loads on the shoe and thrust bearing, respectively, was as follows:

<u>No. of Drops</u>	<u>Load-lb.</u>	<u>Drop Height</u>	<u>Remarks</u>
50	1	one inch	Disassemble and examine
20	3	one inch	
10	5	one inch	Disassemble and examine
10	7	one inch	

Shaft speed 38,500 rpm at rub impact

The test results are described briefly in the following paragraphs and summarized in Tables 8 -14.

5.2.1. 900 F. Tilting Pad Journal Bearing Tests at High Speed Chrome Oxide Coated Pad vs. Chrome Oxide Coated Journal

The initial film thickness, at speed, was about 0.5 mils. After the first 50 impacts of one pound dropped from a height of one inch, the bearing was still running effectively on a 0.5 mils film. After 18 impacts of three pounds dropped from a height of one inch, the bearing was definitely rubbing in contact with the journal.

When the test was disassembled, it was found that the chrome oxide was badly worn and it appeared as though the clearance between the bearing and the journal was gone so that the bearing conformed almost completely to the journal. A photograph of these specimens is shown in Fig. 23. The surfaces had worn very smoothly and the surface finish was not significantly different at the end of the test.

Al₂O₃ Coated Pad vs. Tungsten Carbide Coated Journal

This bearing was running on a film 0.5 mils thick when the shaft was up to speed. After 50 drops of one pound from a height of one inch, the bearing was definitely contacting the journal through the film, so the test was stopped.

Photographs of the surfaces are shown in Fig. 24. The Al_2O_3 coating seemed to be badly worn and the carbide surface was scored. However, the surface roughness measurements shown in Table 9 indicated that the surfaces were not as rough as they appeared to be.

Al_2O_3 Coated Pad vs. Cold-Worked Haynes 25 Journal

Isolated spikes on the probe signals indicated that the bearing might be touching momentarily through the gas film after the fifty drops of one pound. After two drops of three pounds, the pad seemed to "grab" on the journal and was torn completely out of its holder and thrown off of the shaft.

As shown in Fig. 25, the surfaces were badly damaged. A considerable amount of the Al_2O_3 coating was torn off the pad surface and the journal was heavily gouged.

Nickel-Chrome Bonded Chrome Carbide Coated Pad vs. Al_2O_3 Coated Journal

Originally, this coating combination was to have been run at 1400 F. However, as discussed previously, the lack of a good material combination for even 900 F. operation made it advisable to evaluate this combination at 900 F. before considering any higher temperature.

The first attempt to run this combination on TZM substrates was a failure because the test journal shifted on the heat dam while the test was being brought up to speed. This was apparently due to the fact that the TZM molybdenum alloy had such a low coefficient of thermal expansion that the Rene 41 tie bolt, which pulls the test shaft and heat dam up against the support shaft, was loosening up. Since the process of setting up these high speed shafts was very time consuming, it was necessary to substitute a Rene 41 substrate for the TZM. A second shaft with Rene 41 was already partially set up for the next test, so this shaft was coated with chrome carbide and run against an Al_2O_3 coated Rene 41 bearing pad.

This bearing combination ran very effectively through fifty drops of one pound and twenty drops of three pounds. The running film thickness was about 0.5 mils. At the end of the three pound impact test, the probe signals which were monitoring the test shaft indicated that the shaft was beginning to loosen up on the heat dam, so the test had to be stopped at this point.

The bearing and journal surfaces were in excellent condition after this test. Figure 26 shows the appearance of the surfaces. A very faint, polished film of transferred material was visible on the Al_2O_3 coated pad. The journal was highly polished and smooth in the contact area.

5.2.2 1400 F. Tilting Pad Journal Bearing Test at High Speed

Two attempts were made to run high speed rubs on tilting pad bearings at 1400 F. The following combinations were evaluated:

- A. Al_2O_3 coated TD nickel pad vs. Stellite coated Haynes 25 (solution treated) Journal.
- B. An uncoated Rene 41 pad vs. a eutectic $\text{BaF}_2/\text{CaF}_2$ coating on the Rene 41 Journal

Both of these bearings failed before they were completely up to speed. The Al_2O_3 -Stellite combination reached 30,000 rpm and the bearing "grabbed" on the shaft. The Rene 41 combination failed in the same way at 25,000 rpm. As shown in Fig. 27, both bearings apparently contacted the journals at the leading and trailing edges which indicated that they both lost clearance. This could have been the result of centrifugal growth of the shaft. All of these bearing and journal combinations were fabricated to a standard diametral clearance of 1.5 mils. At temperatures up to at least 900 F., this clearance was adequate, but at 1400 F. it would probably have been better to use a larger clearance.

Since the results of the start-stop tests had shown that Al_2O_3 -Stellite combination was not a very promising choice for inert gas applications,

this result simply reinforced the previous findings. Where the Al_2O_3 had contacted the Stellite, metal transfer had taken place from the Stellite to the Al_2O_3 and the Stellite surface was badly gouged.

The Rene 41 pad running against the fluoride coated journal was in much better condition. One area on the journal had lost the coating, but the rest of the surfaces showed very little damage. It is believed that the loss of the coating from the one area of the journal took place while the test was being heated statically to 1400 F. When the bearing had reached temperature, it was found that the bearing was cemented to the journal and the air turbine did not have enough power to break it away. It was necessary to rap the load arm sharply several times before the journal broke loose. This could have been the time that the coating transferred from the journal to the pad. If this was indeed the case, then the pattern of the transferred coating on the loaded zone of the pad showed that there was still adequate clearance between the pad and the journal under static conditions and reinforces the hypothesis that centrifugal growth of the journal had caused the bearing failure, even though calculations predicted a growth of only 0.1 mils radially at this temperature and speed.

5.2.3 900 F. Thrust Bearing Tests at High Speed

For all of these high speed thrust bearing tests, a groove depth of about 1.5 mils was used. The results of these thrust bearing tests are summarized in Tables 11 to 14 and are described in the following paragraphs.

Tungsten Carbide Coated A-286 vs. Al_2O_3 Coated A-286

After the first two drops of 1 pound at 38,500 rpm, the bearing seemed to be going unstable, but it steadied out and ran very smoothly after that momentary lapse. No other problem was encountered during the rest of the fifty drops of 1 pound. The running film thickness was consistent at about 1.5 mils. The same instability was noted when the 3 pound weight was impacted the first time, but the bearing survived the rest of the twenty 3 pound impacts with no problem

The test was shut down and the bearings were examined. The contact was mainly on the outer edges of the bearing as shown in Fig. 28. No significant wear was noted.

The test was then reassembled to run the second series of impact tests. This time, the bearing ran very erratically. At speeds of 15,000 rpm and above, the bearing was so unstable that the test had to be shut down after two impacts with the 5 pound load.

Examination of the bearing showed that the contact area had shifted and now seemed to be concentrated in the center of the bearing, as shown in Fig. 28. This indicated that the bearing had distorted and was now crowned. Since the bearing was operating effectively at temperature before the test was shut down, the results indicated that this distortion occurred during the cooling and reheating of the bearing. To avoid this added complication in the other tests, the entire series of shock loads were run off without shutting down the test in the middle of the run to observe the appearance of the bearings. This seemed to be a reasonable approach particularly in view of the fact that this test had showed so little damage after the first series of shock loads. The problem of distortion was masking the objective of the work which was to study the effect of sliding contacts on bearing performance.

Chrome Oxide on 4340 Steel vs. Chrome Oxide on 4340 Steel

At speed, this bearing was operating on a film thickness of about 2 mils. The entire series of shock loads were run off with no indication of distress.

Photographs of the bearing are shown in Fig. 29. Most of the contact had taken place in the center of the bearing although light scratches over the surface and some polishing at the edges of the bearing indicated that the bearing was reasonably flat.

Al₂O₃ on Haynes 25 vs. Cold-Worked Haynes 25

This bearing had an initial running film thickness of about 1.5 mils at speed. There was no significant change during the first fifty impacts

of 1 pound. After the twenty impacts of 3 pounds, the bearing was still gasborne, but the film thickness had decreased to about 0.5 mils. There was no significant change after the ten drops of 5 pounds, but the bearing seemed to be deteriorating rapidly during the 7 pound impacts. The film thickness decreased to about 0.2 mils after five impacts of 7 pounds and after a total of eight impacts, the bearing was touching lightly at speed. The test was shut down at this point.

Figure 30 shows the appearance of the surfaces. Contact was very uniform across the face of the bearings. The Al_2O_3 coated bearing showed light transfer in the center and heavier metal transfer on the outer edges of the lands. The cold-worked Haynes 25 appeared to be abraded very uniformly across the surface.

Chrome Carbide on TZM vs. Al_2O_3 on TZM

Although this combination was originally scheduled for the 1400 F. evaluation, the lack of promising materials for 900 F use indicated the advisability of running these materials at the lower temperature.

The bearing maintained an operating film thickness of 1.5 mils throughout the complete series of shock loads. As shown in Fig. 31, the bearings were still in good condition at the end of this test. The Al_2O_3 coated thrust collar showed very light transfer and the chrome carbide coated thrust bearing was lightly abraded, but the groove depth measurements indicated that no significant wear had occurred.

5.2.4 1400 F. Thrust Bearing Tests at High Speed

Chrome Carbide on TZM vs. Al_2O_3 on TZM

The specimens from the last 900 F test were relapped and used for this 1400 F evaluation. At speed, the bearing was operating on a film 1.5 mils thick. The fifty drops of 1 pound and the twenty drops of 3 pounds were made without any significant change in bearing performance. After three drops of 5 pounds, the bearing became unstable. It was found that this instability could be eliminated by simply reducing the speed to

about 30,000 rpm and then bringing the bearing back up to 38,500 rpm. The bearing was subjected to the ten drops of 5 pounds and the ten drops of 7 pounds. After every two or three impacts, the bearing would go unstable and it was necessary to go through the speed change in order to bring it back to a stable condition. At the end of the test, the bearing was still running effectively on a film about 1.5 mils thick.

The appearance of the surfaces of the bearings after this test are shown in Fig. 32. Contact was fairly uniform, especially over the grooved area. A thin, transferred film was visible on the Al_2O_3 coated thrust collar. The edges of the chrome carbide lands were worn as would be anticipated because of the periodic instability of the bearing during the test. However, this amount of wear did not appear to have affected the hydrodynamic performance of the bearing.

Nickel-Chrome Alloy on Rene 41 Vs. Eutectic Fluoride Film on Rene 41

No start-up problem was experienced in running this bearing. At 38,500 rpm, the running film thickness was about 1 mil. After twelve impacts of 1 pound, the bearing was touching lightly but steadily, and would not lift completely at any speed.

The appearance of these bearing surfaces is shown in Fig. 33. Most of the coating was removed from the Rene 41 thrust collar. There was some build-up of transferred material on the edge of the bearing which gave the bearing a "dished" shape. The wear measurements were rather strange since they indicated that the bearing was worn about 0.5 mils fairly uniformly across the surface, at least in the land area. The photograph does not show any signs of wear of this magnitude. It is possible that some of the fluoride film had migrated into the bottoms of the grooves and that this was giving an erroneous reading of groove depth.

6. DISCUSSION OF RESULTS

The results of these tests emphasize the problems of isolating the effects of bearing design and geometry from the evaluation of materials. For example, the excellent results obtained in the high speed thrust bearing rub tests, as compared to the high speed tilting pad bearing tests, were apparently due to the fact that the thrust bearings were operating on much thicker films of gas. If the tilting pad bearing had been running on films 1 to 2 mils thick, instead of 0.5 mils, they probably would have also survived a larger number of rubs.

On the other hand, in the start-stop tests the tilting pad bearings could carry a stress of 4 psi, but it was not possible to run the thrust bearings at this high a stress. After a very few start-stop cycles on the thrust bearings at a stress of 4 psi, there was apparently enough surface damage or wear debris generated by the sliding action to penetrate the gas film. A major part of the problem was due to the fact that the flatness of the mating surfaces of the thrust bearing was very critical and that the bearing was operating on a very thin film at this speed. In order to obtain any reasonable data on the thrust bearings, it was necessary to reduce the stresses to lower values. This was not a problem with the tilting pad bearings because the pad and the journal were not conforming surfaces. The tilting pad journal bearing also has interruptions between the pads so that debris can escape as the journal is rotating.

The failures which were encountered in the 1400 F tilting pad high speed tests seemed to be the result of dimensional changes, either warpage of the pads or centrifugal growth of the journal, rather than the sliding behavior of the materials. Nevertheless, the results do represent the first detailed study of the problems which would be encountered in running gas bearings at red heat. If dimensional stability or centrifugal growth was a problem, or an unknown factor, in these tests, it would certainly be an even greater problem in high temperature gas bearing machinery. If the bearings resist sliding damage much more effectively when the film thickness is greater than one mil, then the bearing design and stress level should be selected with this operating film thickness as a minimum goal.

In general, these evaluations demonstrated that it is a much more difficult task to select materials for operation at temperatures above 900 F than it was to choose materials for 500 F. They also showed that the thrust bearings were much more sensitive than the pad journal bearings to damage during starts and stops. Despite these experimental difficulties, the ranking of the materials for sliding effectiveness was very clearly demonstrated in these tests.

Some of the more significant finds of this work were as follows:

1. There is definitely a problem in maintaining dimensional stability at high temperature. As shown in Appendix B, all of the substrate materials, with the exception of the TD nickel, underwent dimensional changes in static heating tests. A specific effort should be made to develop proper heat-treating and aging procedures for these high temperature alloys in order to achieve reasonable stability.

Additional work which has been done at MTI on Contract AF 33(615)-3235 (Ref. 12) indicates that 1200 F is a major transition temperature above which at least some of the superalloys are dimensionally unstable, regardless of heat treatments. While there is not sufficient data to generalize, there is every indication that this may be a limiting item in high temperature gas bearings unless better alloys are found.

It is possible that some of the coatings might be more effective if the substrate materials were more dimensionally stable. However, the improvements would be relative.

2. One coating material combination, Al_2O_3 running against a nickel-chrome bonded chrome carbide, was definitely shown to be a promising combination for use in the temperature range from 900 F to 1400 F.
3. For reliable thrust bearing operation, design stresses above 2.4 psi do not appear to be feasible if a large number of starts and stops are necessary unless better coating materials can be found.
4. During the high speed rubs, the chrome oxide coatings wore at a much higher rate at 900 F, than they did at 500 F. This may have been due to

the fact that the frictional heat which was generated was deteriorating the particle to particle bond. This high wear was not observed with chrome oxide in the tilting pad start-stop tests.

5. In no case was chipping or flaking of the plasma-sprayed groove patterns observed. The only coating bond failure which was observed in these tests occurred at 1400 F during a catastrophic seizure between a tilting pad bearing and the journal. However, some minor edge chipping was noted. This indicated that the edge radii should have been more generous.
6. The poor results obtained with Stellite coatings in the argon environment showed that oxide films were essential for good sliding performance with this material. In air at 1400 F, Stellite coatings had shown considerable promise. The performance of the cold-worked Haynes 25 was probably also hurt by a lack of a protective oxide.
7. The importance of the relative position of the coatings on the sliding behavior of ceramic coatings running against metal-bonded coatings was not clearly demonstrated in these tests. However, the results seem to indicate that it does make a difference.
8. The eutectic fluoride film did give promising results as far as surface protection was concerned, but several problems were encountered in using this coating. The most serious one was the tendency for some constituent to vaporize out of the coating and condense on the capacitance probes.

The results obtained with the fluoride film suggest that thinner films, on the order of 0.1 mils finished thickness, would be less likely to cause problems. If this fluoride film could be applied on the surface of the chrome carbide coating, it should provide an optimum combination.

7.0 RECOMMENDATIONS FOR FUTURE WORK

One promising material combination was isolated as a result of these tests. That combination was a 25 percent nickel chrome-bonded chrome carbide coating mated against a self-bonded Al_2O_3 coating. However, there are still a number of important questions which must be answered before these materials can be used effectively in any practical application. These questions include:

1. The Composition of the Chrome Carbide

There are at least three compositions of chrome carbide that can be applied by plasma spraying. These differ only in the percent of nickel-chrome binder metal. For example, there is a straight, self-bonded chrome carbide with no binder, one with 15 percent nickel chrome binder and one with 25 percent nickel chrome. Some effort should be made to determine if there is a marked difference in performance among these three so that an attempt can be made to optimize the composition.

2. The Importance of Using Al_2O_3 as the Mating Surface

The principal reason for choosing an Al_2O_3 coating to run against chrome carbide was because of the hypothesis that the use of a self-bonded oxide coating on the bearing would inhibit metal transfer and welding. The results of these tests did not bear this out. In one case, where an Al_2O_3 coating on the bearing was run against a tungsten carbide coating on the journal, relatively poor performance was obtained. This was in marked contrast to the excellent results obtained with the Al_2O_3 coated bearing running against a chrome carbide coated journal. As far as the thrust bearing is concerned, it might be better to use chrome carbide mated against itself. In a study of steam-lubricated bearing materials, which was just completed for the AEC, it was found that self-mated chrome carbide appeared to be a promising combination for the thrust bearings in a steam environment. If it was possible to run chrome carbide versus itself in the argon-lubricated thrust bearings, it would be a better choice of materials because the chrome carbide has more ductility and is much less susceptible to chipping than the self-bonded Al_2O_3 would be.

3. Improved Means of Applying Solid Lubricant Films

The results obtained with the NASA eutectic fluoride film, and with the Dow Corning ceramic bonded MoS₂ film, show the importance of developing better techniques for applying these solid lubricants. All of the results which have been obtained to date indicate that the best performance could be obtained if the solid lubricant film was applied over the plasma-sprayed coatings. Then, even if the solid lubricant film was worn away, the hard coatings would still protect the surface. It might also be possible to adjust the porosity of the coating so that more reservoirs would be available to retain the solid lubricant. This would have to be done carefully to strike a reasonable balance between the strength and void content of the plasma coating.

4. The Effect of Temperature

Once the optimum combination of coatings has been established, evaluations should be made over the entire temperature range. Thus far, tests have only been made at 900 F and at 1400 F. The performance should be checked over the entire operating temperature range which presumably includes room ambient. It would be very worthwhile to include some evaluations of chrome oxide versus chrome oxide to compare with the chrome carbide, particularly at temperatures below 600 F, because it is very possible that the chrome carbide might prove to be as good as the chrome oxide, even in the low temperature region. This would be a significant finding because the chrome carbide is easier to apply.

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TABLE 1 MATERIAL COMBINATIONS WHICH WERE USED IN EARLY GAS BEARING WORK

<u>Shaft Material</u>	<u>Bearing Material</u>	<u>Temperature Limitations</u>	<u>Applications</u>	<u>Experience</u>
1. Hardened Steel	Leaded bronze	250 F.	Hydrostatic Bearings	Limited sliding compatibility. Failures at high speeds.
2. Hardened metals or hard chrome plate	Carbon-graphites or metal filled carbon-graphite	To 1000 F. depending on grade	Hydrodynamic	Excellent slow speed sliding behavior. Occasional failures at high speed. Poor thermal expansion characteristics.
3. Hard metal surfaces	Metals with thin resin bonded solid lubricants	To 600 F.	Hydrostatic and hydrodynamic	Excellent as long as coating was intact. Limited wear life.
4. Nitrided Nitralloy	Same as shaft	To 800 F.	Same as above	Unreliable, random failures
5. Hard Metal Surfaces	DU* bonded to metal	500 F.	Same as above	Difficult to retain DU. Limited load carrying capacity. Excellent sliding behavior.
6. Hardened tool steel	Same as shaft	700 F.	Hydrostatic	Poor sliding behavior.
7. Stellite	Hard chrome plate	800 F.	Hydrodynamic	Good for starts and stops.
8. Hard, lapped chrome plate	Monel	700 F.	Hydrodynamic	Good for starts & stops.
9. Hard metal surface	Meehanite	350 F.	Hydrodynamic	Good for starts & stops. Poor corrosion resistance.

*Proprietary composite made by sintering bronze particles on steel sheet and impregnating pores with Teflon and lead.

TABLE 2 SUMMARY OF RESULTS ON START-STOP TESTS
 TILTING PAD JOURNAL BEARINGS AT 900 F. IN ARGON
 Start-Stop Cycle: 0 - 3400 rpm - 0

Tilting Pad	Journal	Torque Values Inch-Pounds Before Test		Running Film Thickness in Mils		Torque Values Inch-Pounds After Test		Total Number of Cycles Run	Rating *
		75 F.	1000 F.	Start	End	1400F.	75 F.		
Chrome Oxide on 4340 Steel	Same as Pad	0.45	0.3	0.75	0.5	Not meas.	0.6	1000	A
Al ₂ O ₃ on Haynes 25	Cold-worked Haynes 25 (no coating)	0.3	0.6	0.5	Failed	0.75	0.75	180	C
Al ₂ O ₃ on A-286 Stainless	Cobalt bonded Tungsten car- bide on A-286 Stainless	0.15	1.5	1.0	0.5	0.9	0.45	1000	A

* Rating: A - Good combination
 B - Fair combination
 C - Poor combination

TABLE 3 SURFACE PROFILE MEASUREMENTS ON START-STOP SPECIMENS
TILTING PAD JOURNAL BEARINGS AT 900 F. IN ARGON

Material Combination	Before Test		After Test		Typical Maximum Values After Test	
	Appearance	Roughness μ in.	Appearance	Roughness μ in.	Peak	Valley
Chrome oxide on 4340 steel pad	Smooth, dull finish	12	Polished con- tact areas	12	50 μ in.	100 μ in.
Chrome oxide on 4340 steel journal	Same as pad	18	Same as pad	15	50 μ in.	150 μ in.
Al_2O_3 on Haynes 25 Pad	Smooth, dull finish	9	Considerable metal transfer at edges	15	500 μ in.	200 μ in.
Cold-worked Haynes 25 Journal (no coating)	Shiny	12	Scored at edges of pad contact	18	100 μ in.	250 μ in.
Al_2O_3 on A-286 stainless pad	Smooth, dull finish	11	Smooth streaks of transferred material	11	25 μ in.	75 μ in.
Cobalt-bonded tung- sten carbide on A-286 journal	Smooth finish	10	Faint, smooth contacts	10	25 μ in.	25 μ in.

TABLE 4 SUMMARY OF RESULTS ON START-STOP TESTS
TILTING PAD JOURNAL BEARINGS AT 1400 F. IN ARGON

Start-Stop Cycle: 0 - 3400 rpm - 0

Tilting Pad	Journal	Torque Values Inch-Pounds Before Test		Running Film Thickness in Mils		Torque Values Inch-Pounds After Test		Total Number of Cycles Run	Rating *
		75 F	1400 F.	Start	End	1400 F.	75 F.		
Al ₂ O ₃ on TZM	Ni-Cr bonded chrome car- bide on TZM	0.3	0.6	0.2	0.4	0.75	Not meas.	1000	A
Al ₂ O ₃ on TD nickel	Stellite 6 on Haynes 25	0.3	0.9	0.3	0.5	0.6	0.3	1000	B
Rene 41 (no coating)	Rene 41 coated with BaF ₂ /CaF ₂	~0.3	1.2	0 to start Improv- ed to ~0.6 mil.	~0.5	1.5	1.2	1000	B

* Rating: A - good combination

B - fair combination

C - poor combination

TABLE 5 SURFACE PROFILE MEASUREMENTS ON START-STOP SPECIMENS
TILTING PAD JOURNAL BEARINGS AT 1400 F. IN ARGON

Material Combination	Before Test		After Test		Typical Maximum Values After Test	
	Appearance	Roughness μ in.	Appearance	Roughness μ in.	Peak	Valley
Al_2O_3 on TZM pad	Smooth, polished	6	Smooth, dull and dark	6	60 μ in.	60 μ in.
Nickel-chrome bonded chrome carbide on TZM journal	Smooth, dull metallic	12	Smooth, dull metallic	10	70 μ in.	100 μ in.
Al_2O_3 on TD nickel pad	Smooth, polished	1-2	Considerable transferred material	8	500 μ in. (edges)	50 μ in. (edges)
Stellite 6 on Haynes 25 journal	Smooth, polished	1-2	Circumferential scratched and transferred material	60	100 μ in. (edges)	300 μ in. (edges)
Rene 41 pad (no coating)	Smooth	8	Considerable transfer of fluoride film in load zone	8	20 μ in.	50 μ in.
Rene 41 Journal coated with $\text{BaF}_2/\text{CaF}_2$	Dull, machine tool finish	20	Smooth except for one area in center where film was removed	38	20 μ in.	200 μ in.

TABLE 6 SUMMARY OF RESULTS OF START-STOP TESTS
THRUST BEARINGS AT 900 F. IN ARGON
Start-Stop Cycle: 0 - 3400 rpm - 0

Material Combination		Performance	Typical Surface Finish μ in. ^(a)		Appearance after Test
Grooved Thrust Bearing	Plain Thrust Collar		Before	After	
Chrome Oxide on 4340 Steel	Chrome Oxide on 4340 Steel	Started test at 2.4 psi stress After 10 cycles, reduced to 2 psi After 75 cycles, reduced to 1.5 psi After 420 cycles, reduced to 1 psi After 615 cycles, would not lift	B ^(b) 10 C ^(c) 10	20 10	Surfaces badly worn, especially on edges of grooves. Considerable abrasion. (See Fig. 16)
Cobalt bonded Tungsten Carbide on A-286 stainless	Al ₂ O ₃ on A-286 stainless	Started test at 3.2 psi stress After 30 cycles, reduced to 2 psi After 120 cycles, reduced to 1.5 psi Completed 1000 cycles at 1.5 psi	B 1 C 2	5 8	Some material transfer to Al ₂ O ₃ . Grooves wearing on edges. Surfaces are in fairly good condition. (See Fig. 17)
Al ₂ O ₃ on Haynes 25 (sol. treated)	Cold-worked Haynes 25 (no coating)	Shaky from start. Tried to run at 1 psi. After 60 cycles at 1 psi - no lift	B 1 C 4	15 80	Grooves badly worn, some metal transfer and abrasion. (See Fig. 18)
Nickel-chrome bonded chrome carbide on TZM molybdenum	Al ₂ O ₃ on TZM	Started test at 2.5 psi Completed 1000 cycles at 2.5 psi Increased stress to 3.2 psi Ran 270 more cycles with no problem	B 2 C 1	4 4	Slight amount of transfer, but surfaces in good condition. Very little wear. (See Fig. 19)

(a) Taken on worn area of grooves

(b) "B" is Thrust Bearing

(c) "C" is Thrust Collar

TABLE 7 SUMMARY OF RESULTS OF START-STOP TESTS
THRUST BEARINGS AT 1400 F. IN ARGON

Start-Stop Cycle: 0 - 3400 rpm - 0

Material Combination		Performance	Typical Surface Finish μ in. ^(b)		Appearance after Test
Grooved Thrust Bearing	Plain Thrust Collar		Before	After	
Nickel-chrome bonded, chrome carbide ^(a) on Rene 41	Al ₂ O ₃ ^(a) on Haynes 25 (sol treated)	Started test at 3.2 psi stress After 50 cycles, reduced to 2.5 psi After 275 cycles, reduced to 1.4 psi Completed 1000 cycles at 1.4 psi	B ^(c) ₃ C ^(d) ₂	6 10	Some transfer to Al ₂ O ₃ . Surfaces in fairly good condition. (See Fig. 20).
Stellite 6 on Haynes 25	Al ₂ O ₃ on TD nickel	Started test at 2 psi stress After 10 cycles, reduced to 1 psi After 90 cycles, no lift	B 1 C 2	30 4	Lands badly worn, some heat checking. (See Fig. 21)
Nickel-chrome alloy on Rene 41	BaF ₂ /CaF ₂ coating on Rene 41	Would not lift initially, even at 1.4 psi After 45 cycles at 1.4 psi, bearing running well. Increased stress to 2 psi after 590 cycles, no lift.	B 1 C 20	20 32	Transfer of fluoride to thrust bearing. Lands slightly worn at edges. (See Fig. 22)

(a) A solid lubricant film containing MoS₂ was applied to these coatings, but most of the film was removed during final lapping, and it probably had no beneficial effect on the results.

(b) Taken on worn area of grooves.

(c) "B" is Thrust Bearing

(d) "C" is Thrust Collar

TABLE 8 SUMMARY OF RESULTS OF HIGH SPEED RUB TESTS^(a)
TILTING PAD JOURNAL BEARING TESTS AT 900 F. IN ARGON

Speed - 38,500 rpm

Material Combination		Initial Film Thickness	Results	
Tilting Pad	Journal			
Chrome oxide coated 4340 steel	Chrome oxide coated 4340 steel	0.5 mils	Survived	50 drops of 1 pound 18 drops of 3 pounds Rubbing contact at speed after this sequence. (See Fig. 23)
Al ₂ O ₃ coated A-286 stainless	Cobalt bonded Tung- sten carbide on A-286 stainless	0.5 mils	Survived	50 drops of 1 pound Touching at speed at this point. (See Fig. 24)
Al ₂ O ₃ coated Haynes 25	Cold-worked Haynes 25 (no coating)	0.6 mils	Survived	50 drops of 1 pound. (Suspicion of touching at speed at this point.) 2 drops of 3 pounds. Pad seized. (See Fig. 25)
Al ₂ O ₃ coated Rene 41	Ni-Cr bonded chrome carbide on Rene 41	0.5 mils	Survived	50 drops of 1 pound 20 drops of 3 pounds Still running effectively on 0.5 mil film. (See Fig. 26)

- (a) 50 drops of one pound from 1" high
20 drops of three pounds from 1" high
10 drops of five pounds from 1" high
10 drops of seven pounds from 1" high

TABLE 9 SURFACE PROFILE MEASUREMENTS OF HIGH SPEED RUB SPECIMENS
TILTING PAD JOURNAL BEARING TESTS AT 900 F. IN ARGON

Material Combination	Before Test		After Test		Maximum Values After Test	
	Appearance	Roughness μ in.	Appearance	Roughness μ in.	Peak	Valley
Chrome oxide on 4340 steel pad	Smooth, dull	12	Worn smoothly	14	250 μ in.	100 μ in.
Chrome oxide on 4340 steel journal	Smooth, dull	18	Worn smoothly	14	150 μ in.	200 μ in.
Al ₂ O ₃ on A-286 stainless pad	Smooth, dull	11	Worn smoothly some polish- ed transfer	19	25 μ in.	150 μ in.
Cobalt-bonded tungsten carbide on A-286 stainless journal	Smooth, shiny	10	Numerous abrasion scratches	18	50 μ in.	100 μ in.
Al ₂ O ₃ on Haynes 25 pad	Smooth, dull	10	Part of Al ₂ O ₃ coat- ing failed	--	--	--
Cold-worked Haynes 25 Journal (no coating)	Smooth, shiny	5	Badly damaged	--	--	--
Al ₂ O ₃ on Rene 41 pad	Smooth, dull	10	Light transfer, polished	6	10 μ in.	60 μ in.
Nickel-chrome bonded chrome carbide on Rene 41 journal	Dull, metallic	45	Polished in contact area	15	50 μ in.	350 μ in.

TABLE 10 SUMMARY OF RESULTS OF HIGH SPEED RUB TESTS
TILTING PAD JOURNAL BEARING TESTS AT 1400 F. IN ARGON

Speed 38,500 rpm

Material Combination		Results
Tilting Pad	Journal	
Al ₂ O ₃ coated TD Nickel	Stellite 6 coated Haynes 25 (solution treated)	Bearing seized on journal at 30,000 rpm while test being brought up to speed. Part of Al ₂ O ₃ coating torn away from TD nickel substrate. Stellite coating badly gouged. (See Fig. 27)
Rene 41 (no coating)	BaF ₂ /CaF ₂ film on Rene 41	Bearing seized on journal at 25,000 rpm while test being brought up to speed. One area on journal lost the coating. Rest of surfaces in very good condition. (See Fig. 27)

TABLE 11 SUMMARY OF RESULTS OF HIGH SPEED RUB TESTS
THRUST BEARING TESTS AT 900 F. IN ARGON

Speed 38,500 rpm

Material Combination		Initial Film Thickness	Results
Grooved Thrust Bearing	Plain Thrust Collar		
Tungsten carbide on A-286 stainless	Al ₂ O ₃ on A-286 stainless	1.5 mils	Survived: 50 drops of 1 pound 20 drops of 3 pounds Stopped test to examine and photograph surfaces. When bearing was brought up to temperature again, it would not lift properly because of warpage.
Chrome oxide on 4340 steel	Chrome oxide on 4340 steel	2.0 mils	Survived. 50 drops of 1 pound 20 drops of 3 pounds 10 drops of 5 pounds 10 drops of 7 pounds (Did not stop test to examine surfaces after 20 drops of 3 pounds.)
Al ₂ O ₃ on Haynes 25 (solution treated)	Cold-worked Haynes 25	1.5 mils	Survived: 50 drops of 1 pound 20 drops of 3 pounds (film thickness now 0.5 mils) 10 drops of 5 pounds 8 drops of 7 pounds (bearing touching) (Did not stop test in the middle to examine surfaces.)
Nickel-chrome bonded chrome carbide on TZM	Al ₂ O ₃ on TZM	1.5	Survived: 50 drops of 1 pound 20 drops of 3 pounds 10 drops of 5 pounds 10 drops of 7 pounds (Did not stop test in the middle to examine surfaces.)

TABLE 12 SURFACE PROFILE MEASUREMENTS OF HIGH SPEED RUB SPECIMENS
THRUST BEARING TESTS AT 900 F. IN ARGON

Speed 38,500 rpm

Material Combination	Before Test (a)		After Test (a)		Crowning Due to Wear of Grooves
	Appearance	Roughness	Appearance	Roughness	
Tungsten carbide on A-286 thrust bearing	Polished	4	Light abrasion	9 (peaks 60 μ in.)	None
Al ₂ O ₃ on A-286 stainless thrust collar	Smooth	4	Smooth transfer	4 (peaks 0)	(See Fig. 28)
Chrome oxide on 4340 thrust bearing	Dull, smooth	10	Light abrasion in center.	13 (center) (peaks 80 μ in.)	None
Chrome oxide on 4340 thrust collar	Dull, smooth	5	Light abrasion in center	36 (center) (peaks 40 μ in.)	(See Fig. 29)
Al ₂ O ₃ on Haynes 25 thrust bearing	Smooth	4	Light transfer at center and edges.	20 (peaks 20 μ in.)	None
Cold-worked Haynes 25 thrust collar	Polished	1	Uniform fine abrasion.	8 (peaks 20 μ in.)	(See Fig. 30)
Nickel-chrome bonded chrome carbide on TZM thrust bearing	Smooth, dull	8	Fine abrasion.	12 (peaks 40 μ in.)	None
Al ₂ O ₃ on TZM thrust collar	Smooth	4	Uniform polished transfer	4 (peaks 40 μ in.)	(See Fig. 31)

(a) Microinches

TABLE 13 SUMMARY OF RESULTS OF HIGH SPEED RUB TESTS
THRUST BEARING TESTS AT 1400 F. IN ARGON

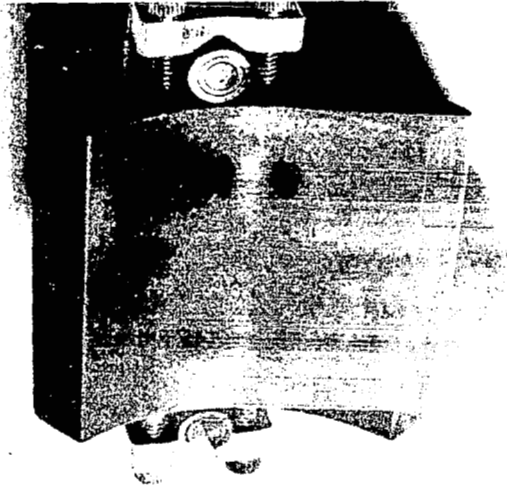
Speed 38,500 rpm

Material Combination		Initial Film Thickness	Results
Grooved Thrust Bearing	Plain Thrust Collar		
Nickel-chrome bonded chrome carbide on TZM	Al_2O_3 on TZM	1.5 mils	Survived. 50 drops of 1 pound 20 drops of 3 pounds * 10 drops of 7 pounds * *Bearing went unstable several times, but stabilized when speed was dropped and then brought back to 38,500 rpm.
Nickel-chrome alloy groove pattern on Rene 41	$\text{BaF}_2/\text{CaF}_2$ eutectic on Rene 41	1.0 mils	Survived. 12 drops of 1 pound (Would not lift after this.)

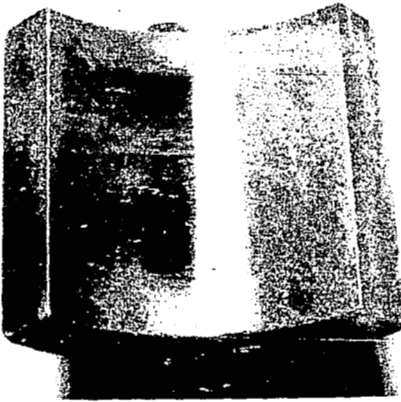
TABLE 14 SURFACE PROFILE MEASUREMENTS OF HIGH SPEED RUB SPECIMENS
THRUST BEARING TESTS AT 1400 F. IN ARGON

Speed 38,500 rpm

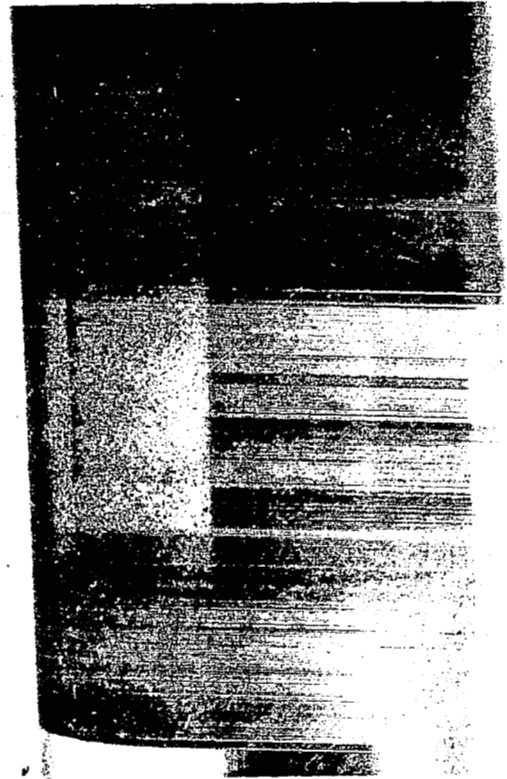
Material Combination	Before Test		Appearance	Roughness μ in.	Crowning Due to Wear of Grooves
	Appearance	Roughness μ in.			
Nickel-chrome bonded chrome carbide on TZM thrust bearing	Dull, smooth	8	Uniform Abrasion	16 (peaks 200 μ in. valleys 300 μ in.)	.0004"
Al ₂ O ₃ coating on TZM thrust collar	Smooth	4	Smooth, polished transfer	8 (peaks 40 μ in. valleys 120 μ in.)	-- (See Fig. 32)
Nickel-chrome alloy groove pattern on Rene 41 thrust bear- ing.	Polished	1	Very light abrasion in center and on outer edges of grooves	5 (peaks 20 μ in. valleys 10 μ in.)	Dished, .0005" high at edge of grooves worn .0005" toward center.
BaF ₂ /CaF ₂ eutectic film on Rene 41 thrust collar	Dull green film	14	Film gone off most of bearing except outer edges.	14 (peaks 40 μ in. valleys 40 μ in.)	-- (See Fig. 33)



(a) Pad After First Series of High Speed Rubs

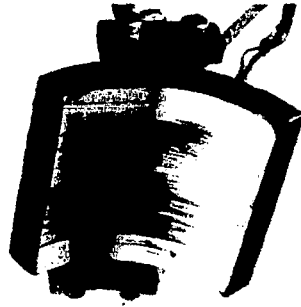


(b) Test Pad

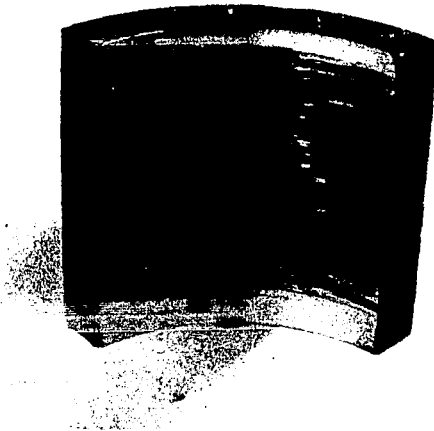


(c) Test Shaft

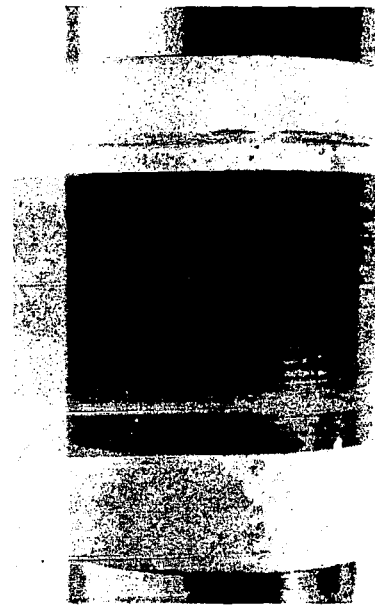
Fig. 1 Contact Surfaces on Tilting-Pad Bearing and Shaft after High Speed Rubs. Chrome Oxide Coated Pad vs Chrome Oxide Coated Journal. Run in Argon at 60,000 rpm. Test Temperature 500 F.



(a) Carbide Pad after First Sequence of Shock Loads



(b) Carbide Pad



(c) Al_2O_3 Shaft

Fig. 2 Contact Surfaces on Tilting-Pad Bearing and Journal after High Speed Rubs. Nickel Bonded Tungsten Carbide Coated Pad vs Al_2O_3 Coated Shaft. Run in Argon at 60,000 rpm Test Temperature 350°F

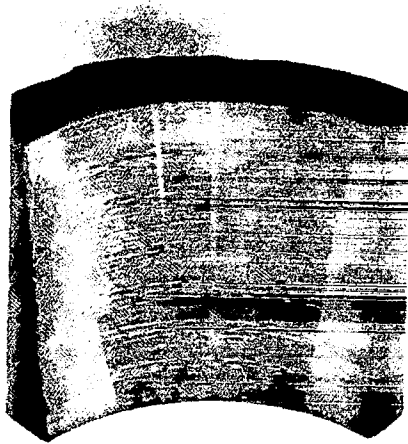
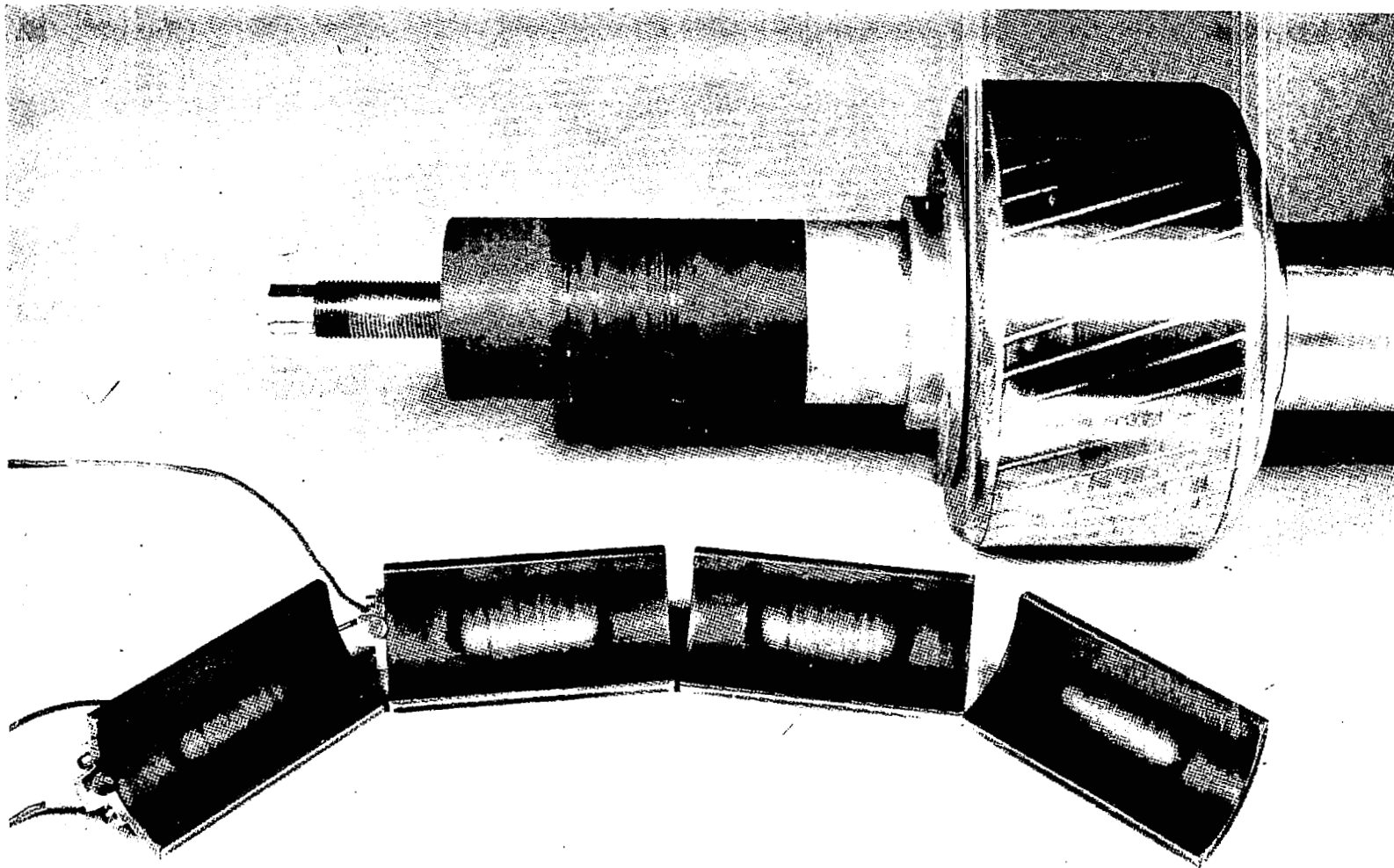


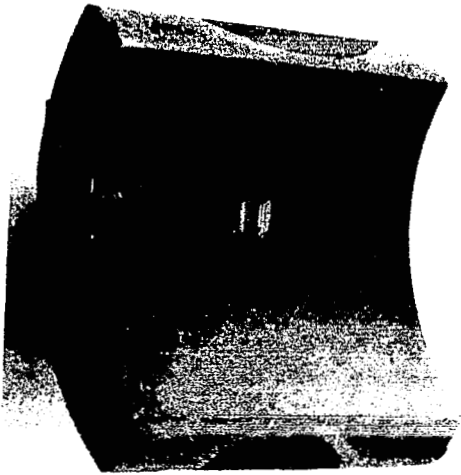
Fig. 3 Surface of Tilting Pad Bearing After 100 High Speed
Rubs at 48,000 rpm in Ambient Air

Bearing Coating: 0.003" chrome oxide
plus
0.0001" resin-bonded MoS_2

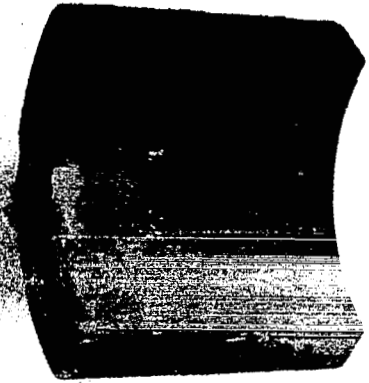


-63-

Fig. 4 Chrome Oxide Coated Hydrodynamic Journal and Tilting Pad Bearings from Navy Shock Test Machine After 1400 Impacts. Bearing Still Functioning Satisfactorily.



High Density Coating



Lower Density Coating

Fig. 5 Surface Appearance of Chrome Oxide Coated Pads with Different Density Coatings Both Pads Subjected to One Hundred High Speed Rubs at 48,000 rpm in Air

Fig. 6 "Layout Drawing of High Temperature Hydrodynamic Bearing Test Rig for Materials Evaluations".

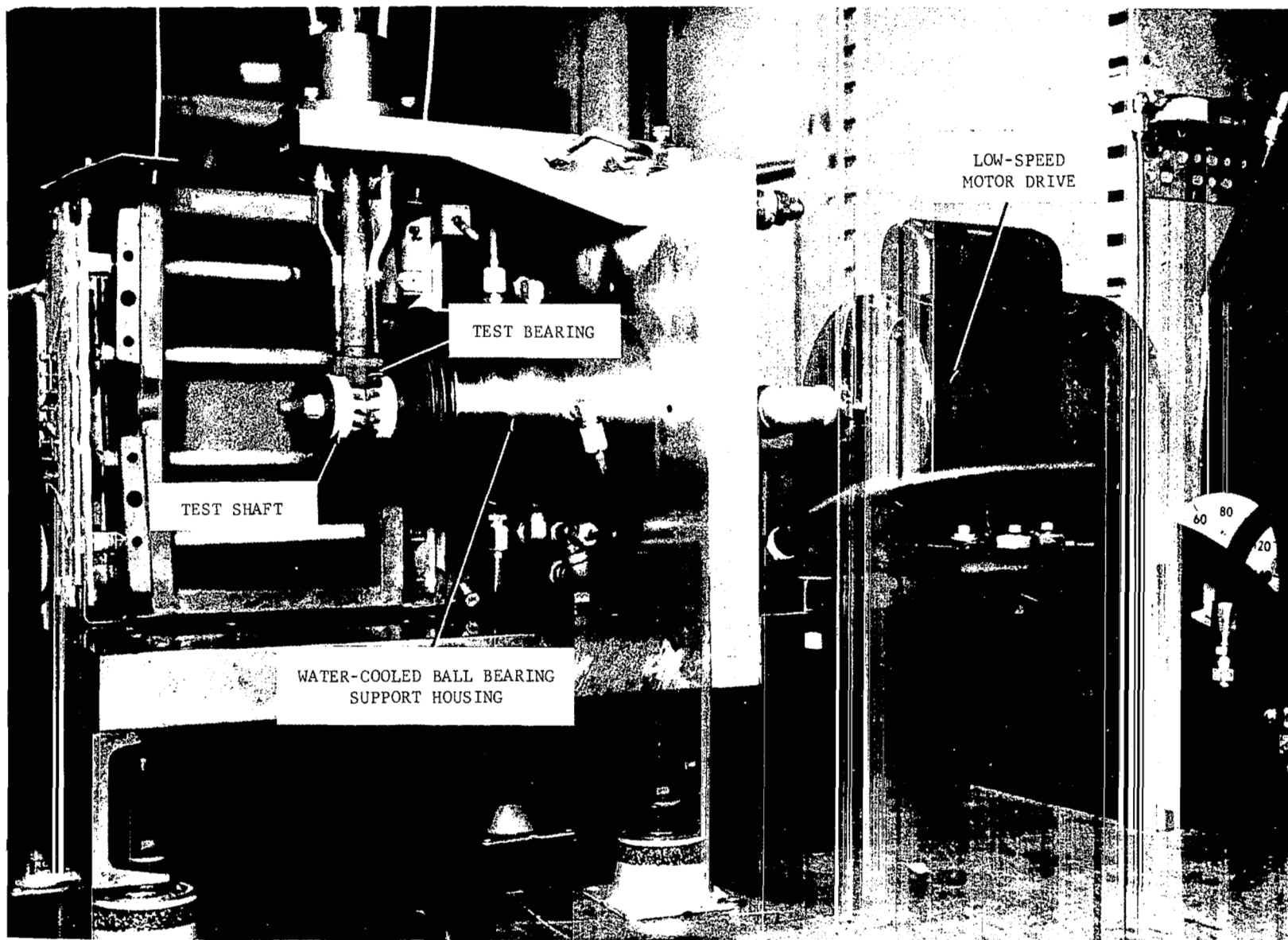


Fig. 7 Partially Assembled View of Test Rig Set Up for Tilting Pad Journal Bearing Evaluations. Enclosure for Argon Blanketing is Not Shown.

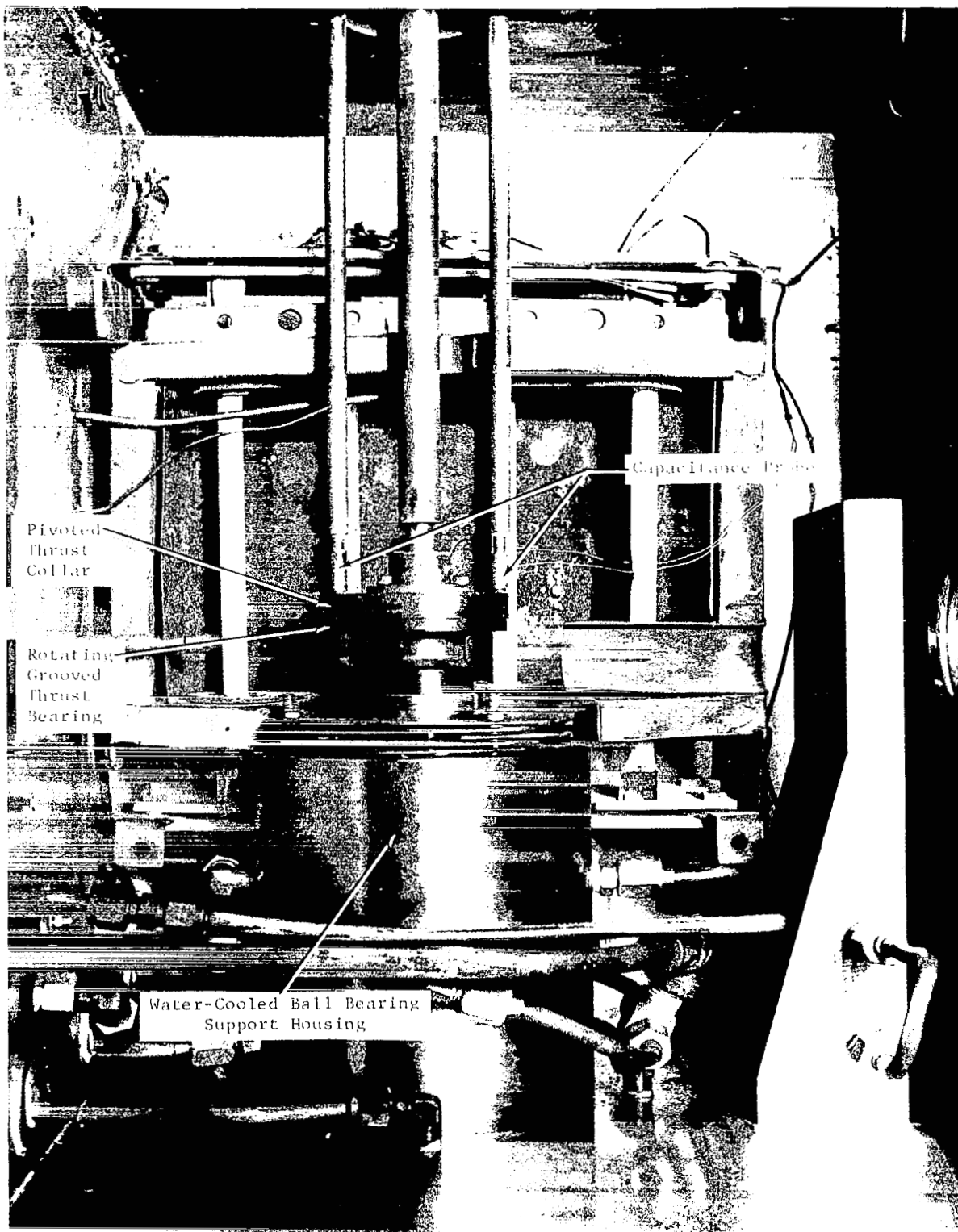


Fig. 8 View of Partially Assembled Test Rig Set Up for Thrust Bearing Evaluations. One Side of the Enclosure has been Removed.

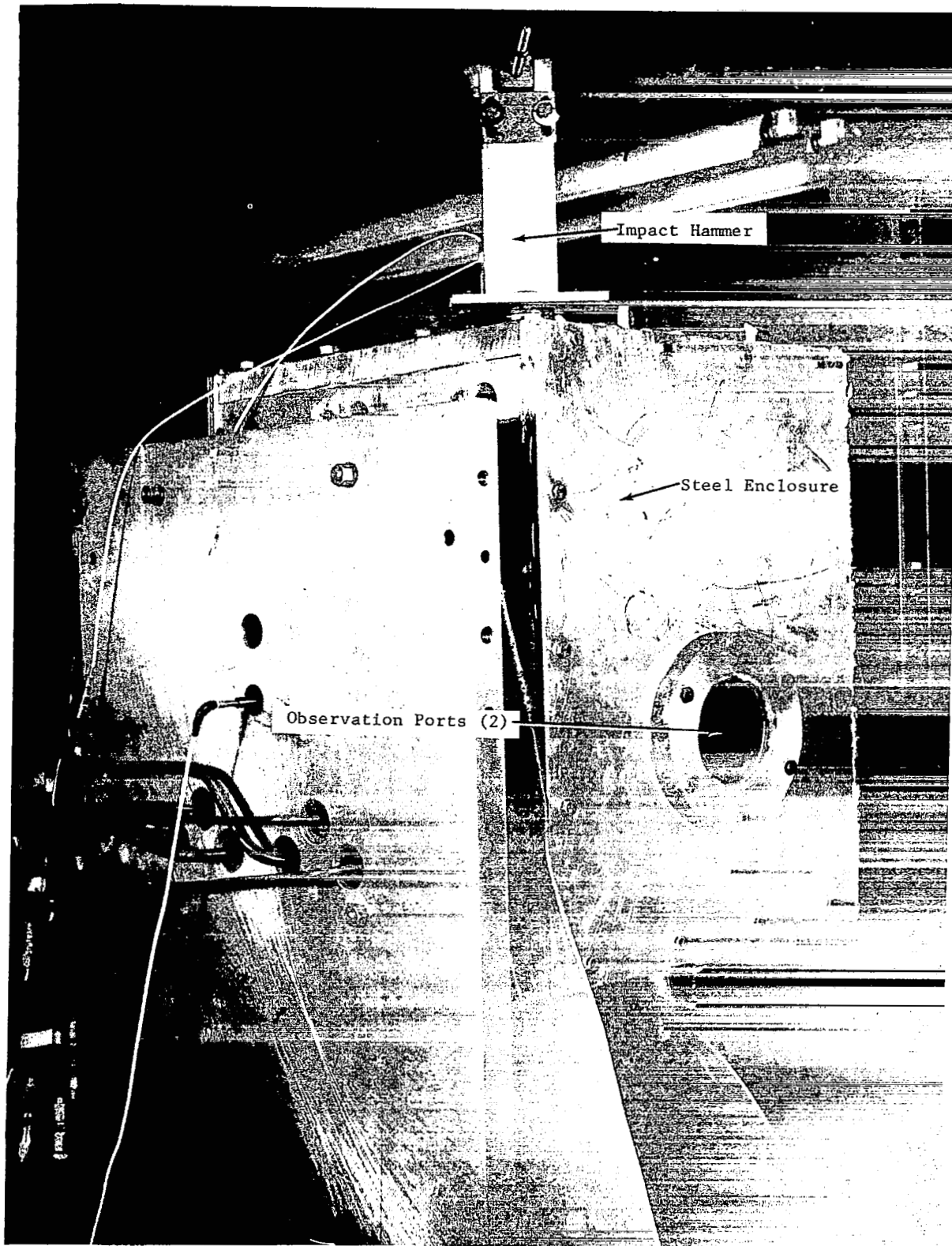


Fig. 9 Overall View of Test Rig Set Up for Thrust Bearing Evaluations in an Argon Environment

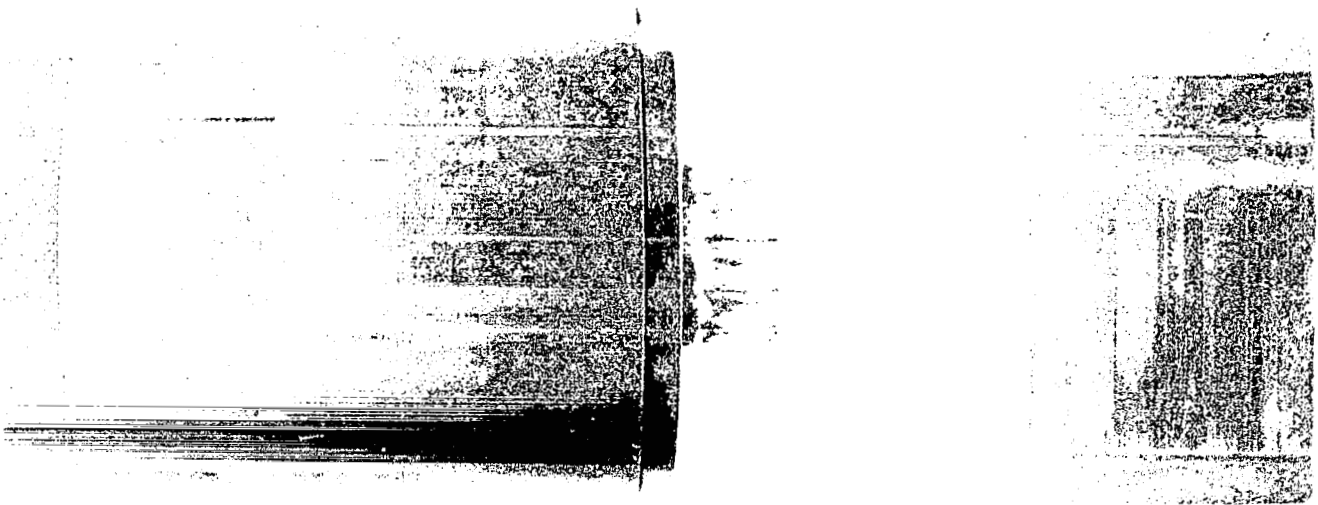


Fig. 10 Chrome Oxide Coated Tilting Pad Bearing vs. Chrome Oxide Coated Journal.
After 1000 Starts and Stops at 900 F in Argon.



Fig. 11 Al_2O_3 Coated Tilting Pad Bearing vs. Tungsten Carbide Coated Journal.
After 1000 Starts and Stops at 900 F in Argon.

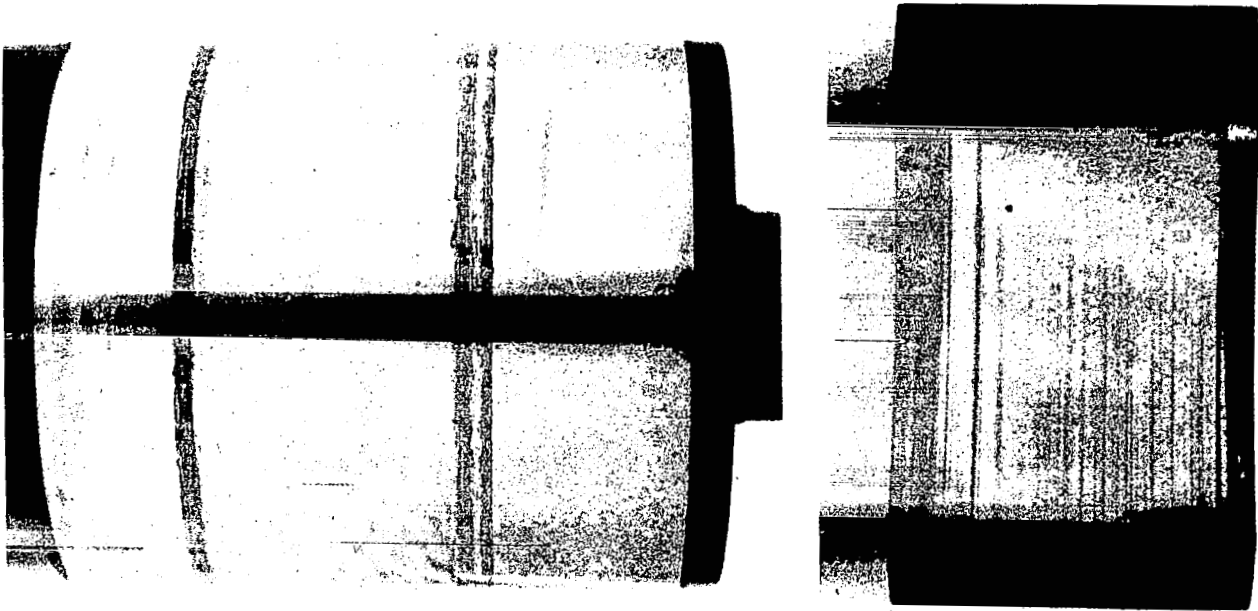


Fig. 12 Al₂O₃ Coated Tilting Pad Bearing vs. Uncoated Cold-Worked Haynes 25 Journal.
Failed After 180 Starts and Stops at 900 F in Argon.

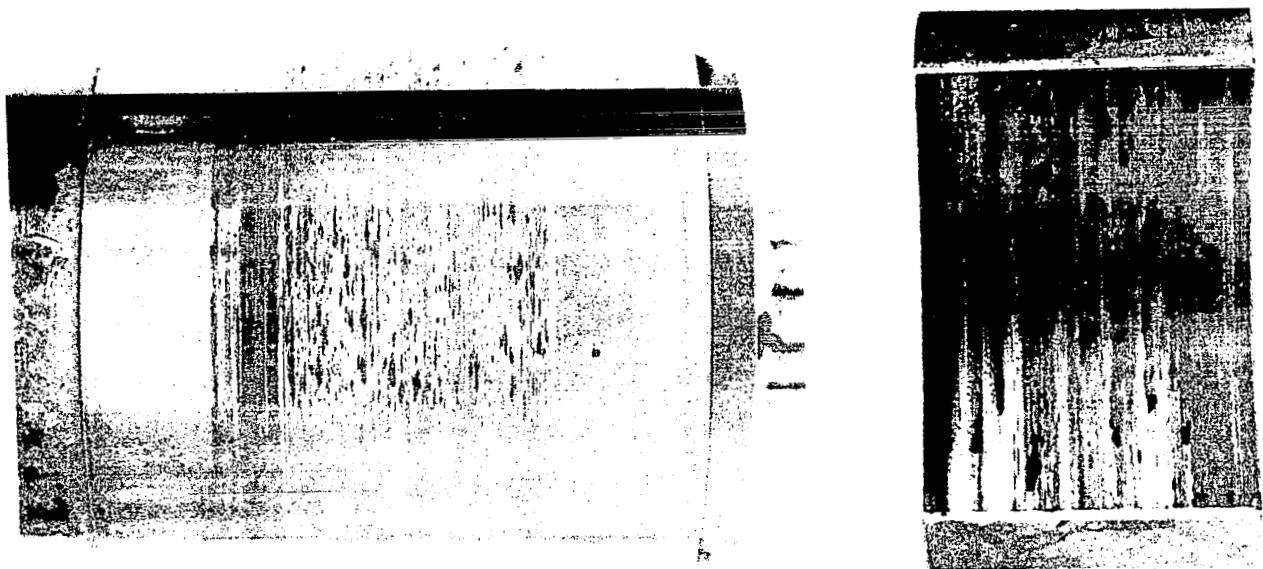


Fig. 13 Al_2O_3 Coated Tilting Pad Bearing vs. Stellite Coated Journal.
After 1000 Starts and Stops at 1400 F in Argon.

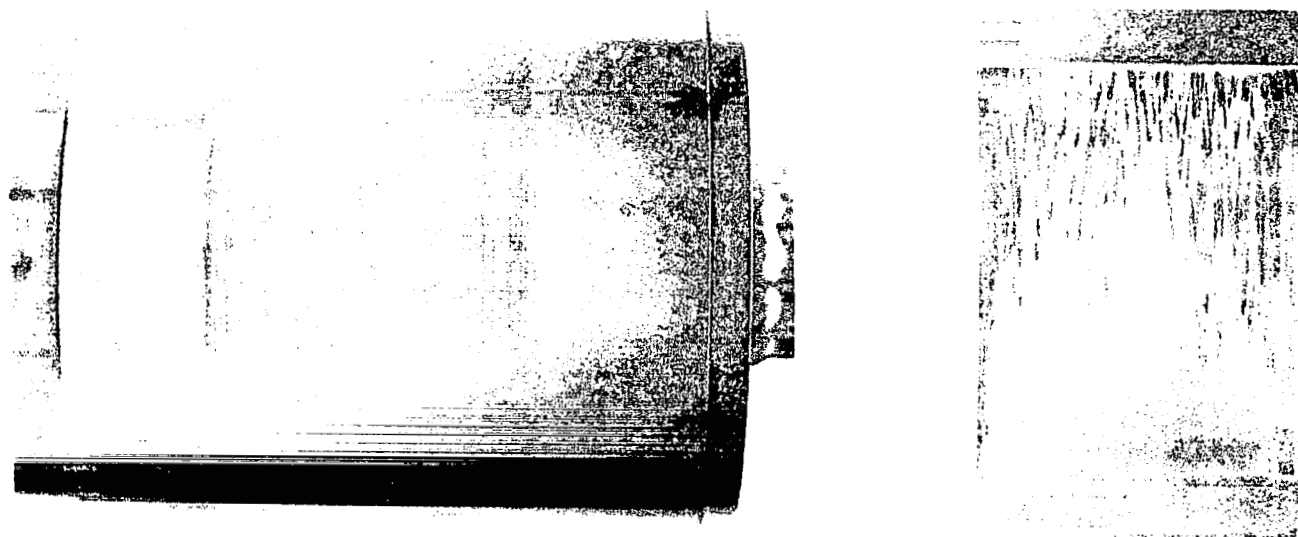


Fig. 14 Al₂O₃ Coated Tilting Pad Bearing vs. Chrome Carbide Coated Journal.
After 1000 Starts and Stops at 1400 F. in Argon.

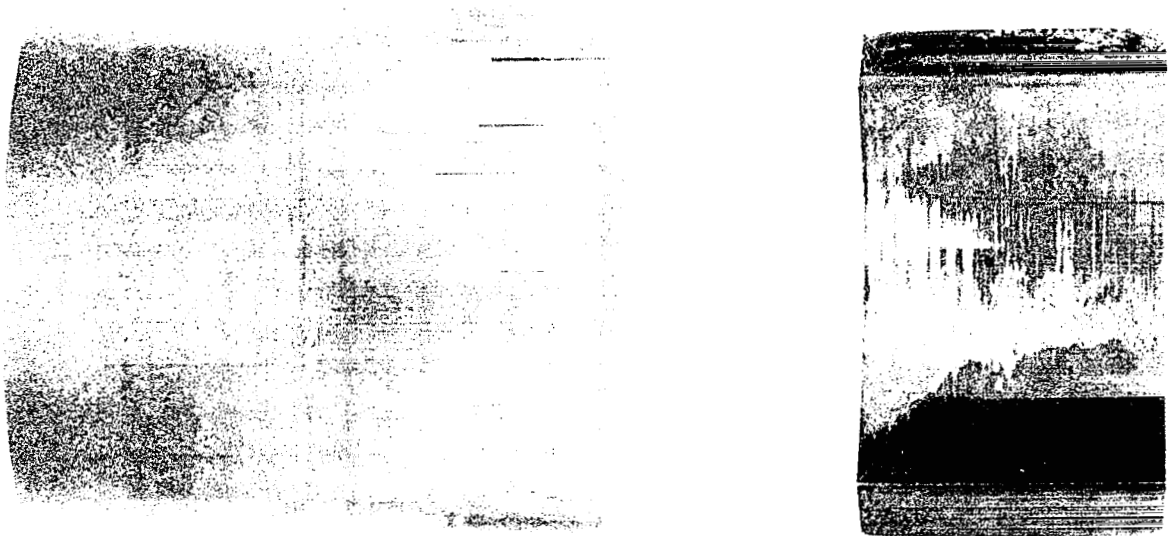
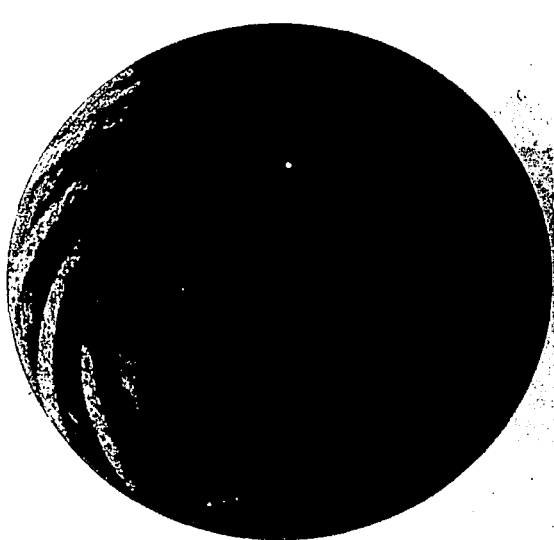
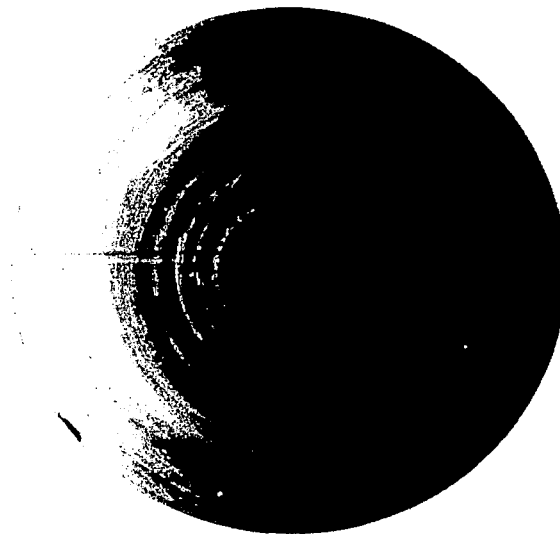


Fig. 15 Uncoated Rene 41 Tilting Pad Bearing vs. Fluoride Film Coating on Rene 41 Journal. After 1000 Starts and Stops at 1400 F in Argon.



Grooved Thrust Bearing



Thrust Collar

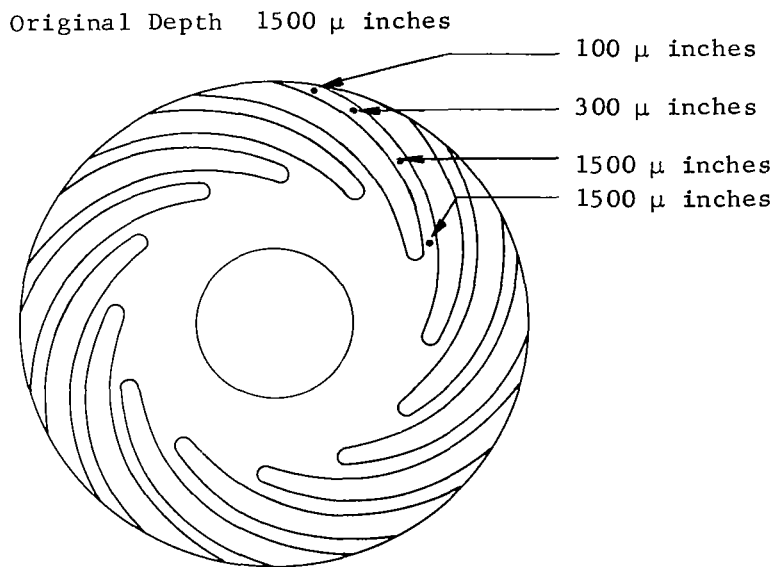
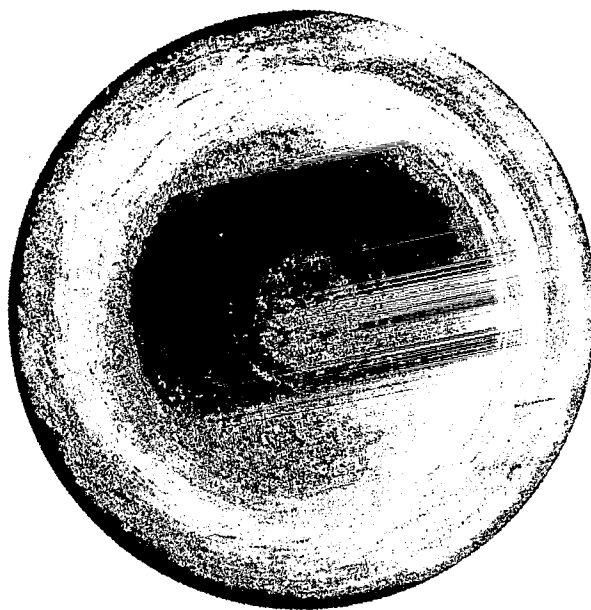


Fig. 16 Chrome Oxide Coated Grooved Thrust Bearings vs. Chrome Oxide Coated Thrust Collar. Failed After 615 Starts and Stops at 900 F in Argon. Final Stress 1 psi.



Grooved Thrust Bearing



Thrust Collar

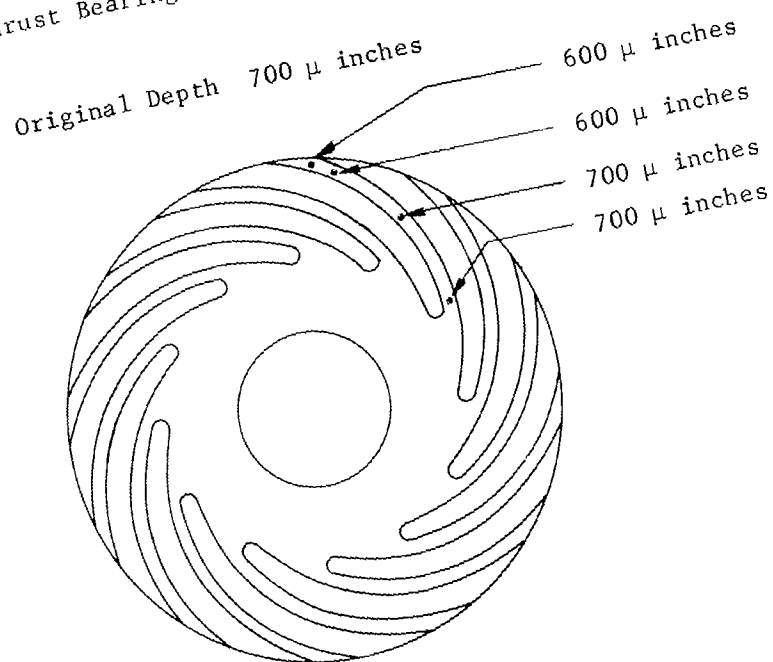
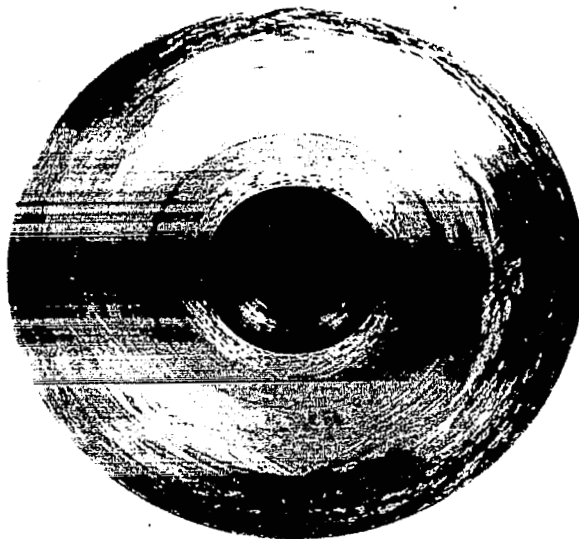


Fig. 17 Tungsten Carbide Coated Grooved Thrust Bearing vs. Al_2O_3 Coated Thrust Collar. Completed 1000 Starts and Stops at 1.5 psi Stress in Argon at 900 F.



Grooved Thrust Bearing



Thrust Collar

Original Depth 800 μ inches

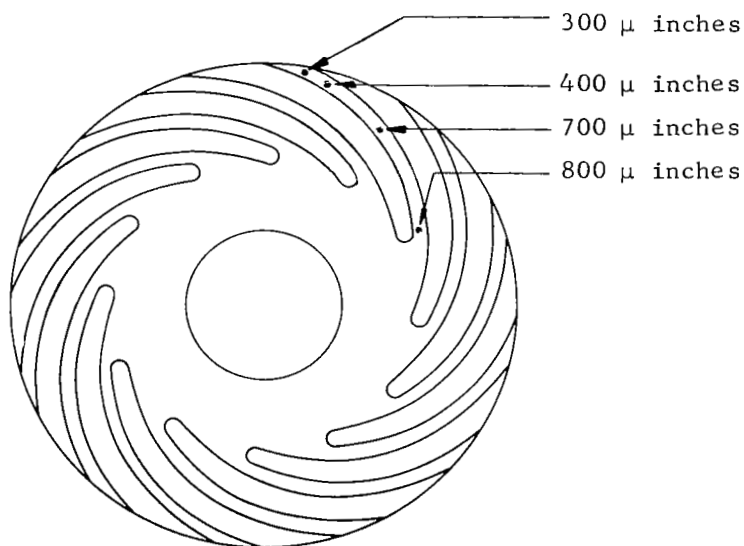
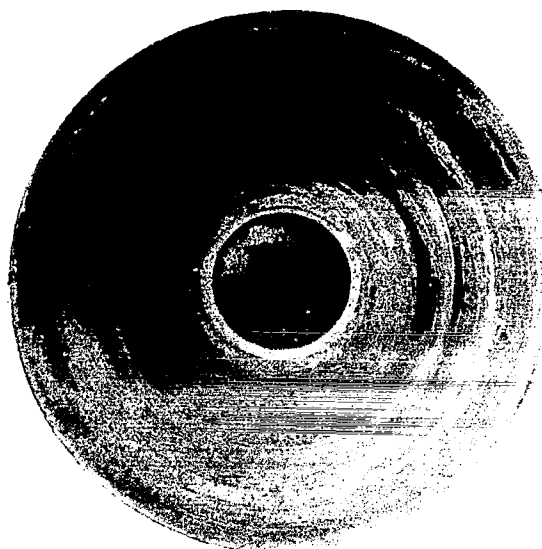


Fig. 18 Al_2O_3 Coated Grooved Thrust Bearing vs. Uncoated Cold-Worked Haynes 25 Thrust Collar. Failed After 60 Starts and Stops at 900 F in Argon. Final Stress 1 psi.



Grooved Thrust Bearing



Thrust Collar

Original Depth 800 μ inches

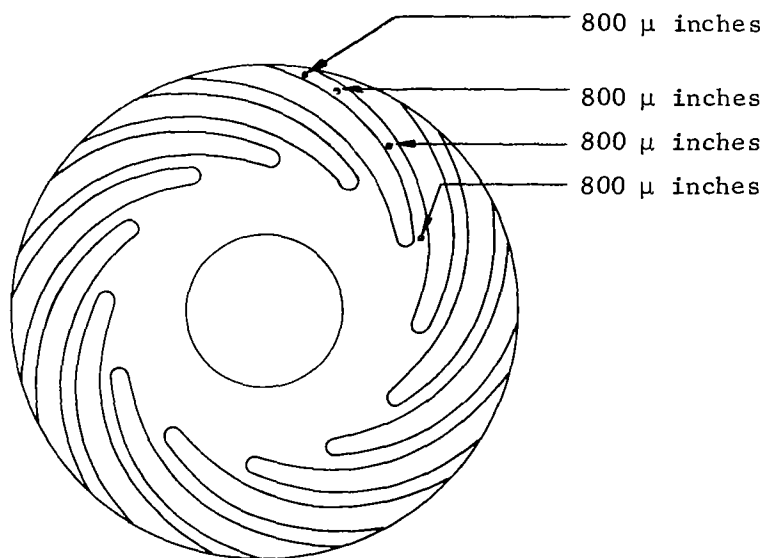
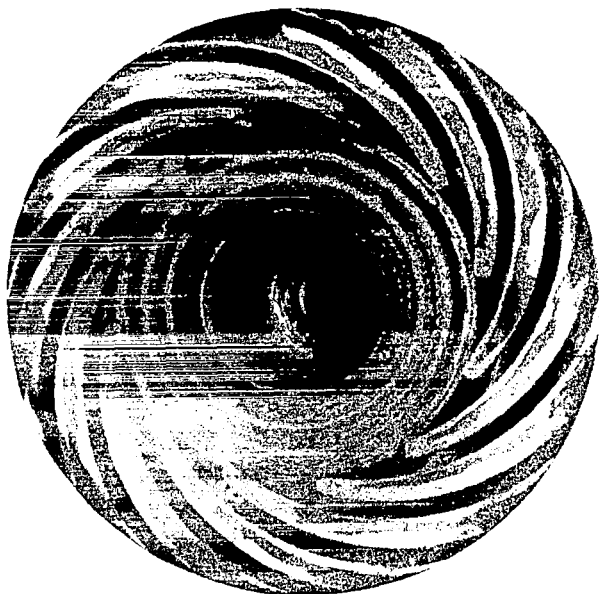
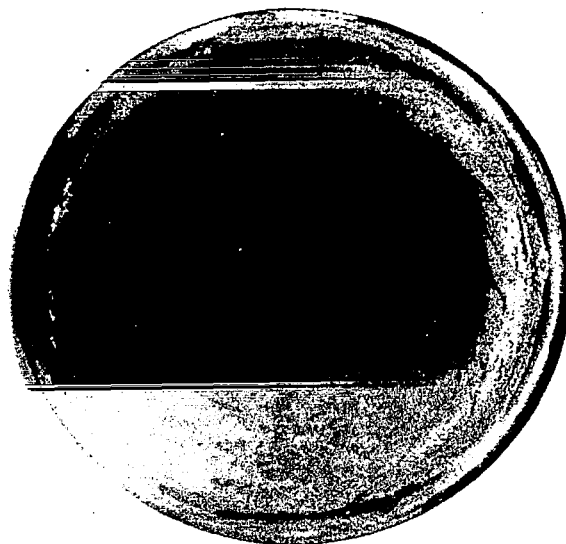


Fig. 19 Chrome Carbide Coated Grooved Thrust Bearing vs. Al_2O_3 Coated Thrust Collar. Completed 1000 Starts and Stops at 2.5 psi. Stress and an Additional 270 Starts and Stops at 3.2 psi in Argon at 900 F.

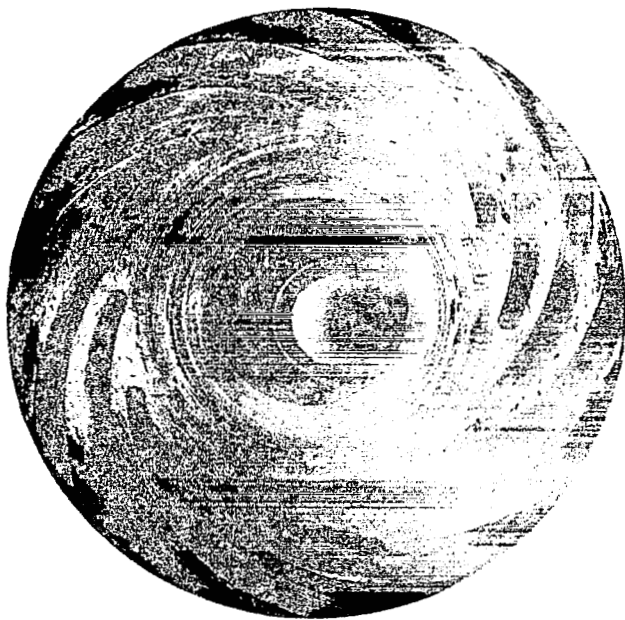


Grooved Thrust Bearing

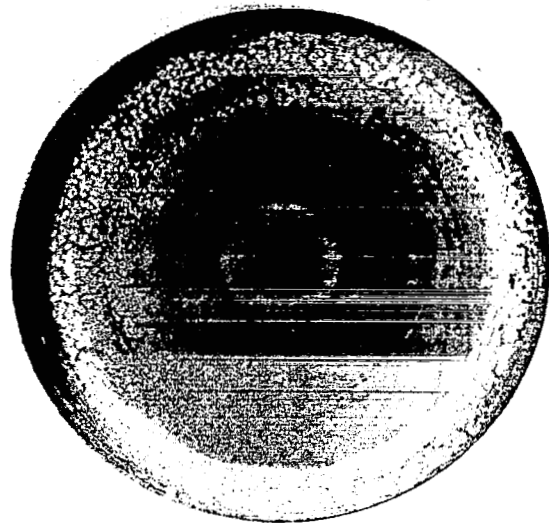


Thrust Collar

Fig. 20 Chrome Carbide Coated Grooved Thrust Bearing vs.
 Al_2O_3 Coated Thrust Collar. Both Surfaces were Coated
 with Solid Lubricant Film and Subsequently Lapped.
 Completed 1000 Starts and Stops at 1.4 psi at 1400 F in Argon.



Grooved Thrust Bearing



Thrust Collar

Original Depth 700 μ inches

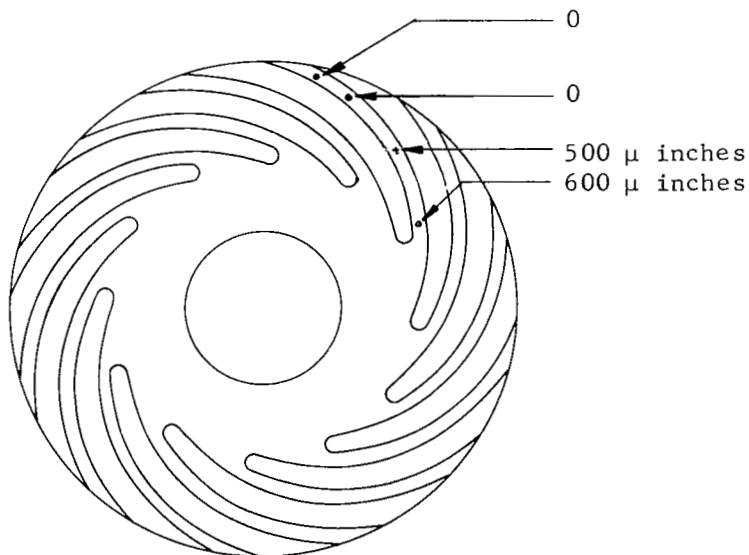
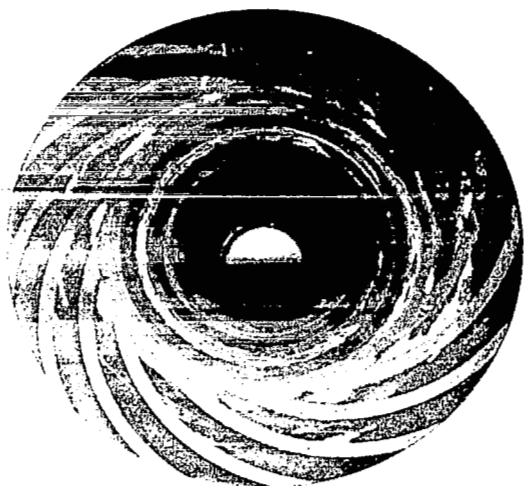
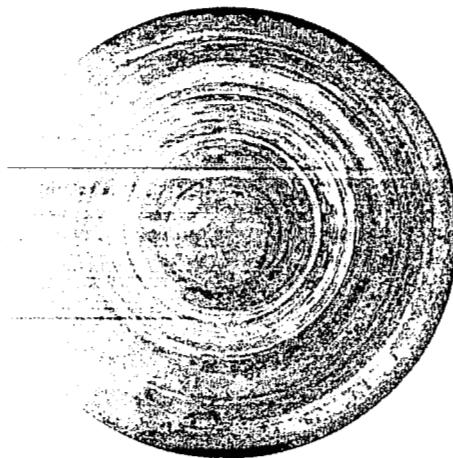


Fig. 21 Stellite 6 Coated Grooved Thrust Bearing vs. Al_2O_3 Coated Thrust Collar. Failed After 90 Starts and Stops at 1 psi in Argon at 1400 F.



Thrust Bearing After Test



Coated Thrust Collar After Test

Original Depth $700\ \mu$ inches



Thrust Bearing After Cleaning
Off Transferred Material

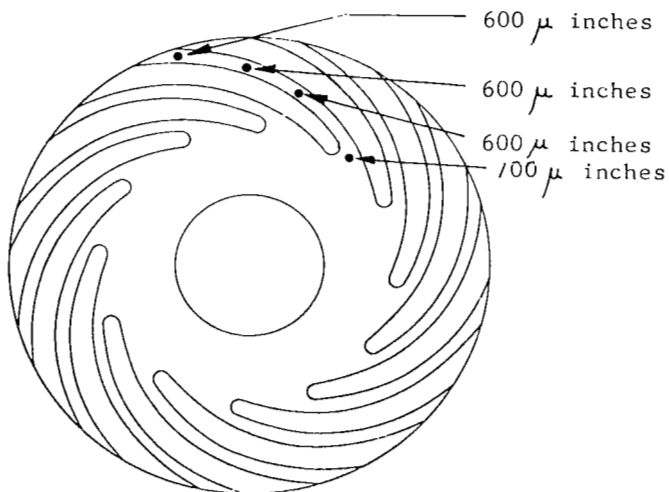


Fig. 22 Nickel-Chrome Alloy Coated Grooved Thrust Bearing vs. Eutectic Fluoride Coating on Rene 41 Thrust Collar. Would Not Carry 2 psi after 590 Start-Stop Cycles at 1400 F in Argon.

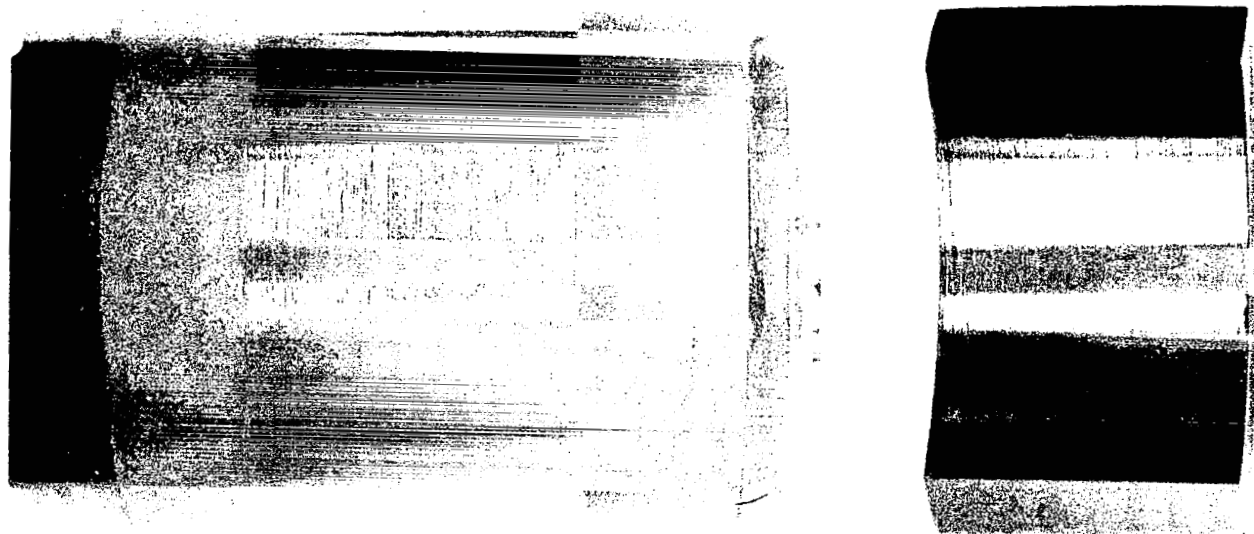


Fig. 23 Chrome Oxide Coated Tilting Pad Bearing vs. Chrome Oxide Coated Journal. After High Speed Rubs at 900 F in Argon.

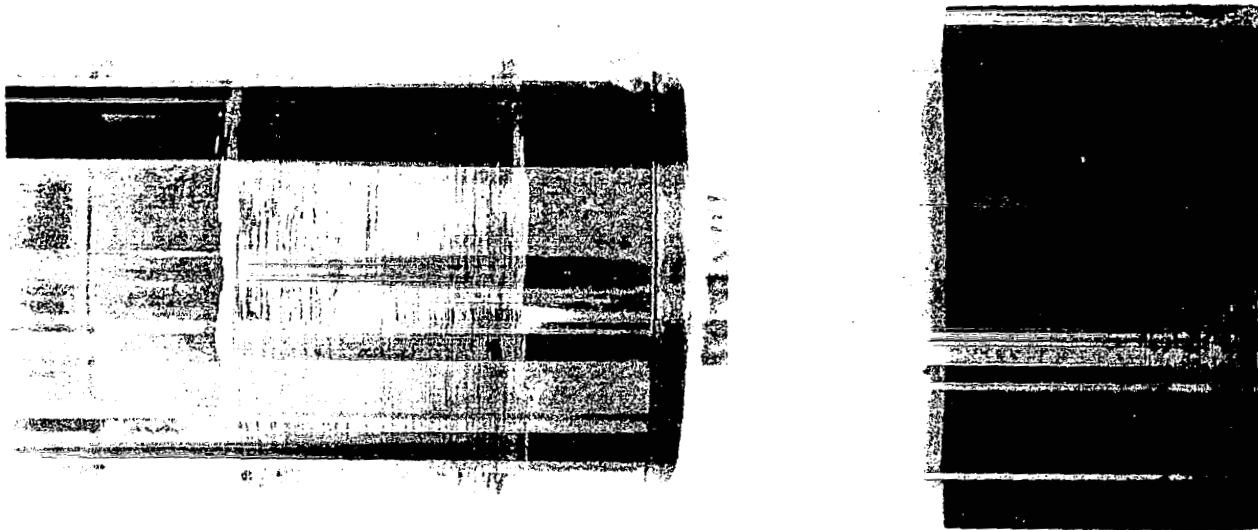


Fig. 24 Al_2O_3 Coated Tilting Pad Bearing vs. Tungsten Carbide
Coated Journal. After High Speed Rubs at 900 F in Argon.

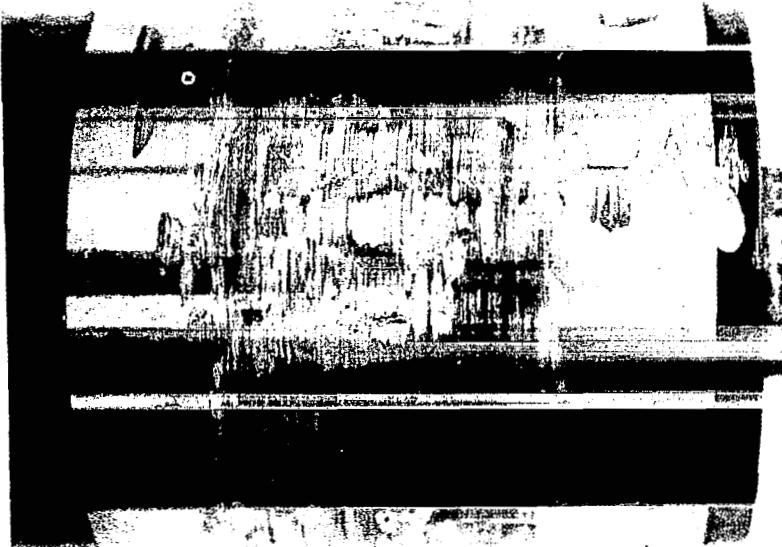


Fig. 25 Al₂O₃ Coated Tilting Pad Bearing vs. Uncoated Cold-Worked Haynes 25 Journal. After High Speed Rubs at 900 F in Argon.

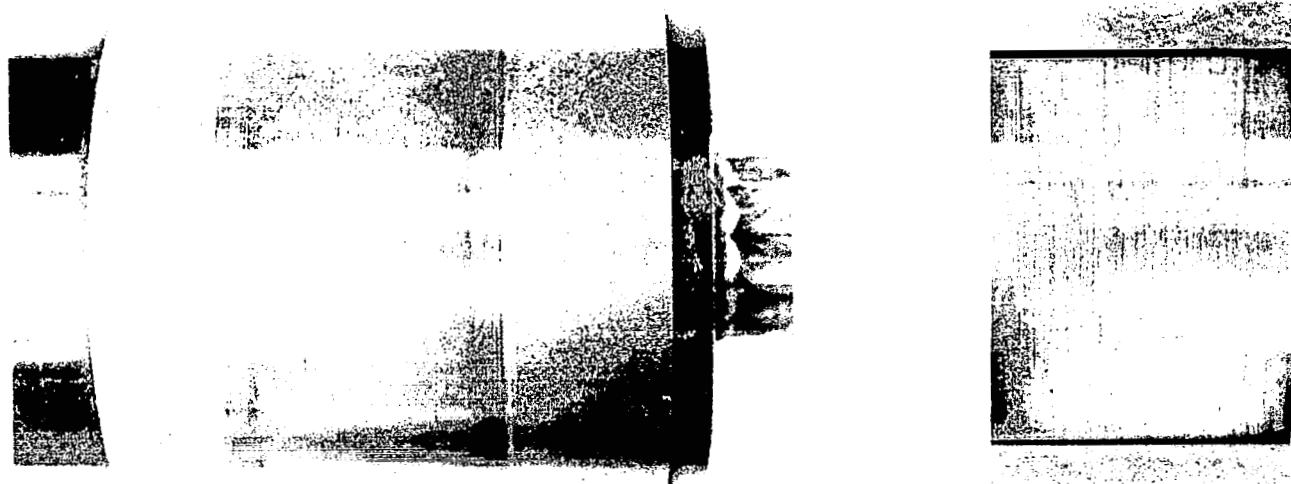
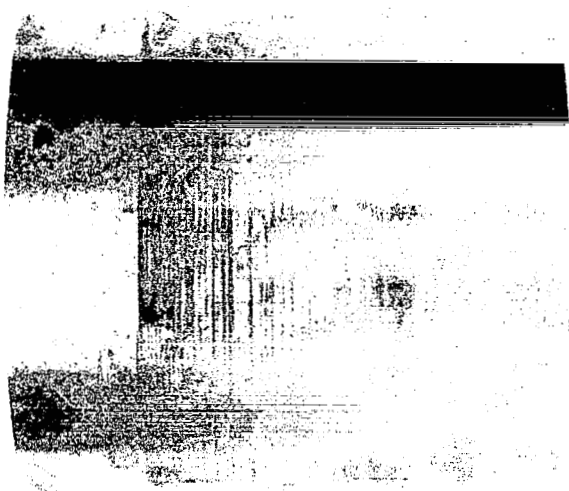
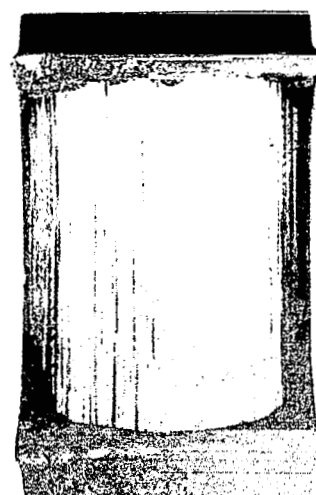


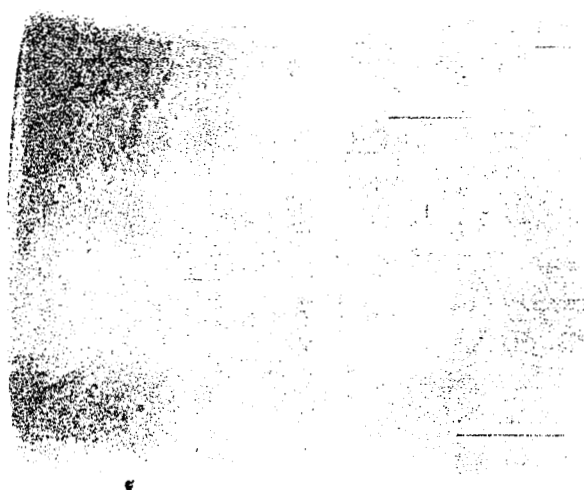
Fig. 26 Al₂O₃ Coated Tilting Pad Bearing vs. Chrome Carbide Coated Journal. After High Speed Rubs at 900 F in Argon.



Stellite 6 Coated Journal



Al_2O_3 Coated Pad Bearing

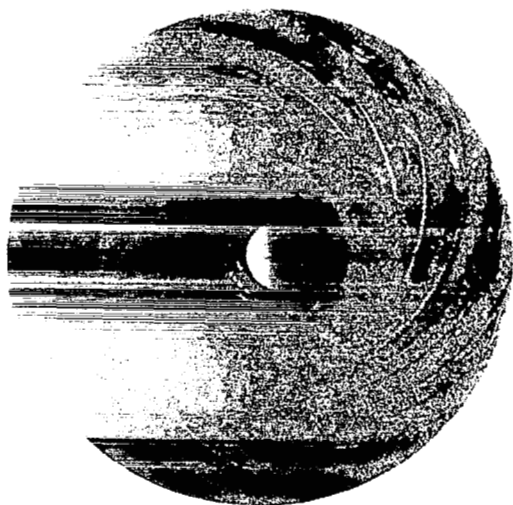


$\text{CaF}_2/\text{BaF}_2$ Coated Journal

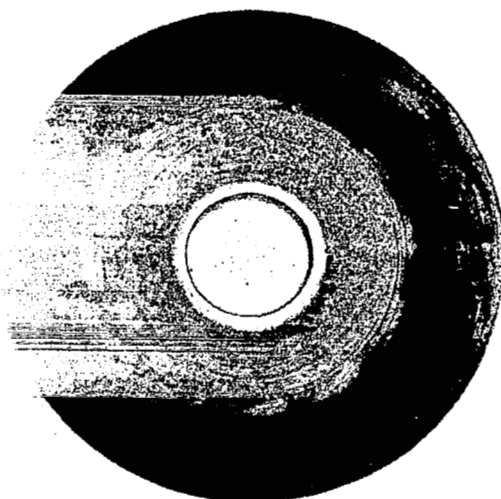


Rene 41 Pad Bearing

Fig. 27 Tilting Pad Bearings and Journals. After High Speed Failures at 1400 F in Argon.

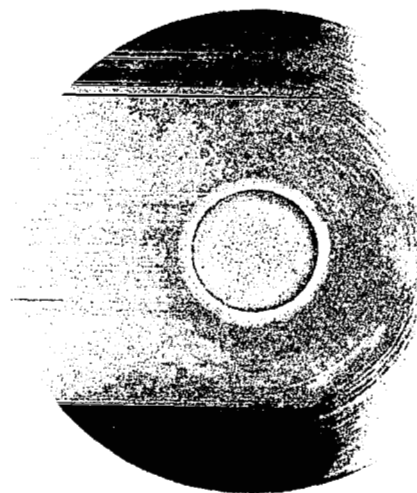
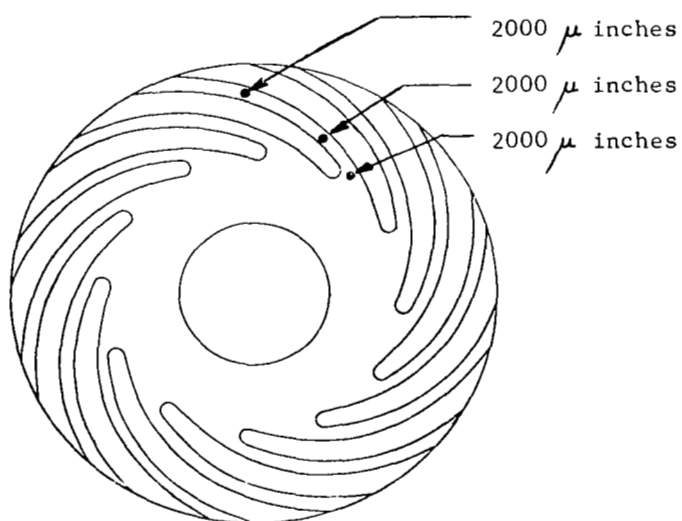


Carbide Coating Thrust Bearing
After Second Series of Impacts



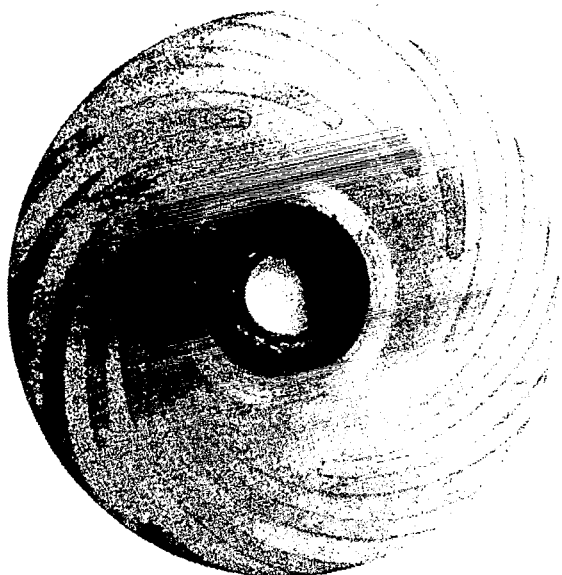
Al_2O_3 Coated Thrust Collar
After First Series of Impacts

Original Depth 2000μ inches

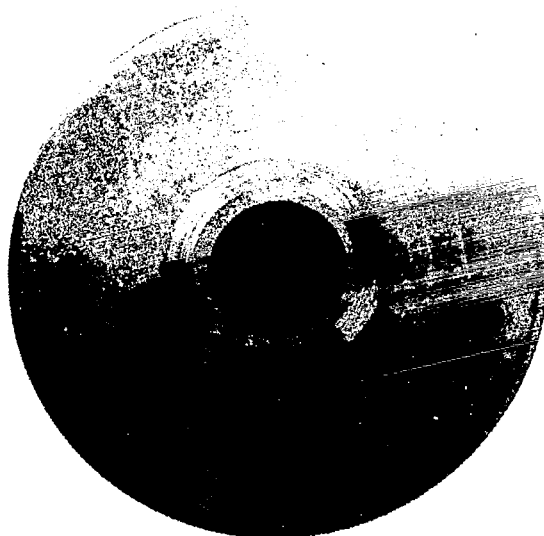


Al_2O_3 Coated Thrust Collar
After Second Series of Impacts

Fig. 28 Tungsten Carbide Coated Grooved Thrust Bearing vs. Al_2O_3
Coated Thrust Collar. After High Speed Rubs at 900 F in Argon at 38,500 rpm.



Grooved Thrust Bearing



Thrust Collar

Original Depth 1500 μ inches

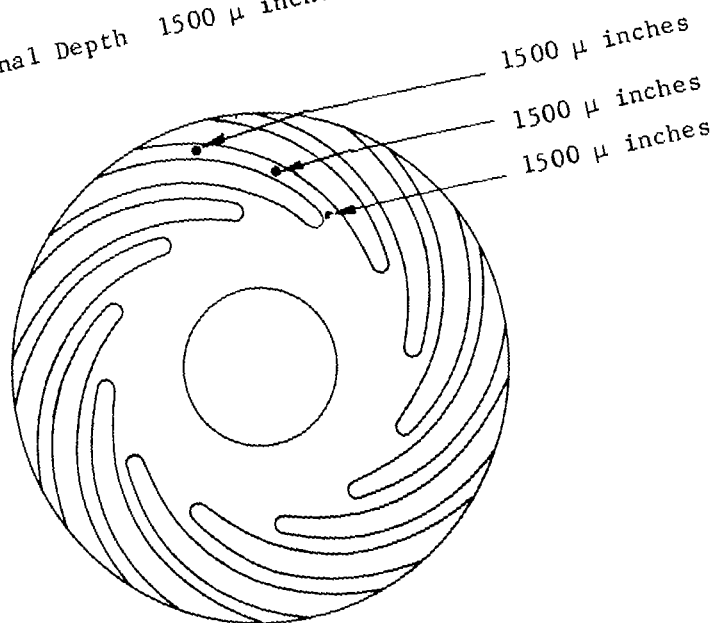
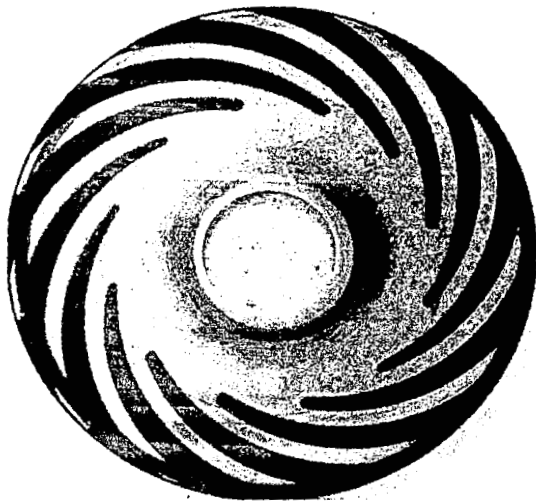


Fig. 29 Chrome Oxide Coated Grooved Thrust Bearing vs Chrome Oxide Coated Thrust Collar. After High Speed Rubs at 900 F in Argon at 38,500 rpm.



Grooved Thrust Bearing



Thrust Collar

Original Depth 1200 μ inches

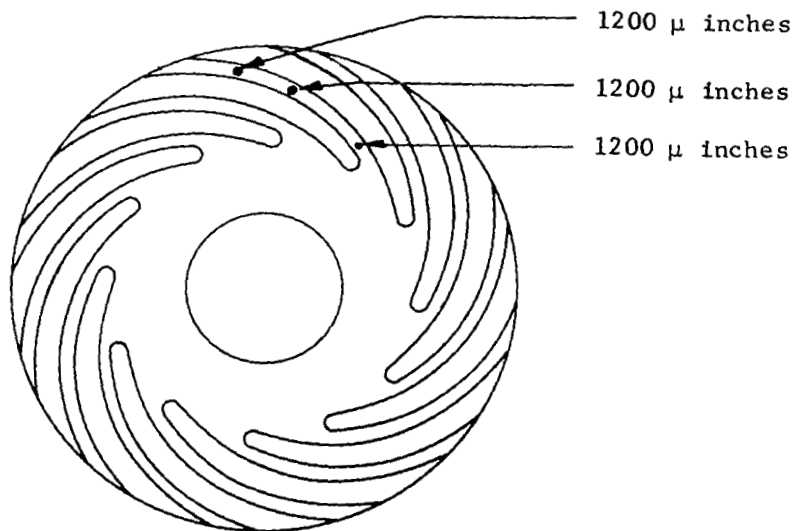


Fig. 30 Al_2O_3 Coated Grooved Thrust Bearing vs. Cold-Worked Haynes 25 Thrust Collar. After High Speed Rubs at 900 F in Argon at 38,500 rpm.



Grooved Thrust Bearing



Thrust Collar

Original Depth 1600 μ inches

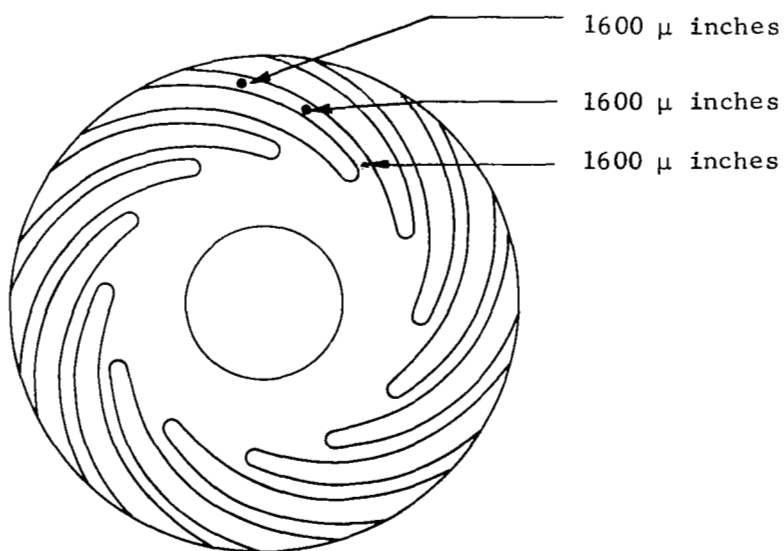
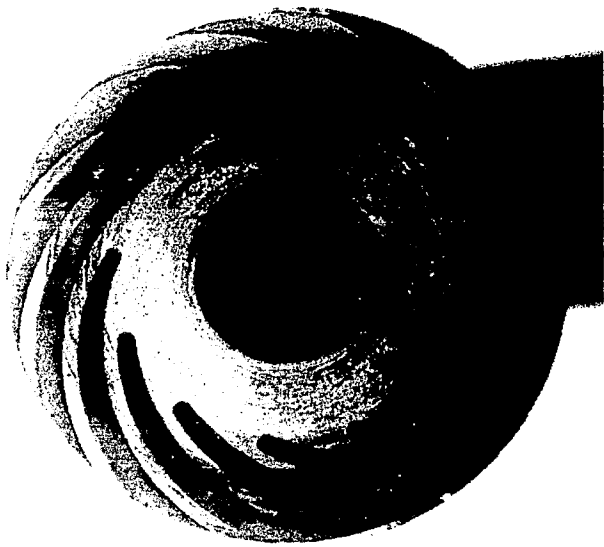
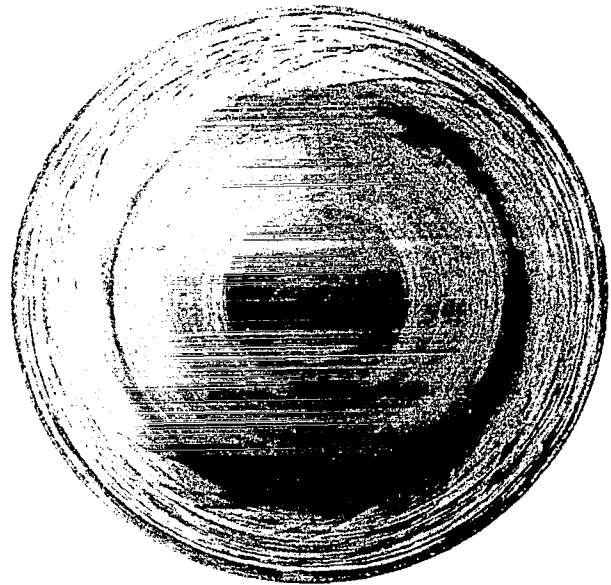


Fig. 31 Chrome Carbide Coated Grooved Thrust Bearing vs. Al_2O_3 Coated Thrust Collar. After High Speed Rubs at 900 F in Argon 38,500 rpm.



Grooved Thrust Bearing



Thrust Collar

Original Depth 1600 μ inches

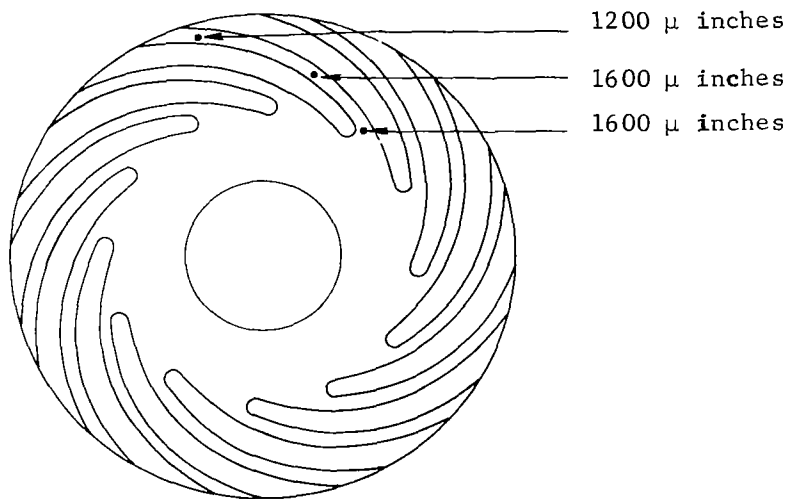
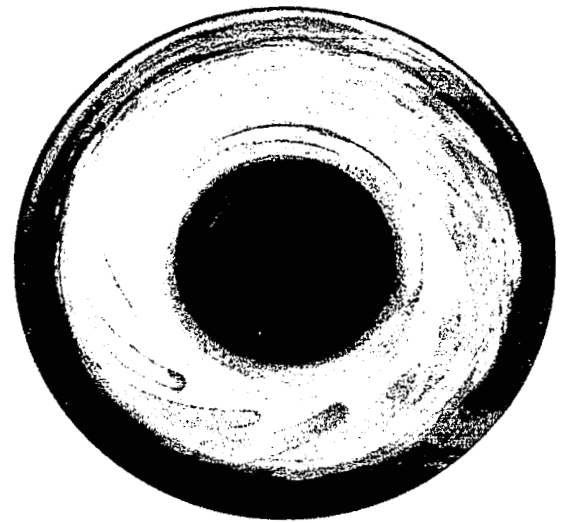


Fig. 32 Chrome Carbide Coated Groove Thrust Bearing vs. Al_2O_3 Coated Thrust Collar. After High Speed Rubs at 1400 F in Argon at 38,500 rpm.



Grooved Thrust Bearing



Thrust Collar

Original Depth 1500 μ inches

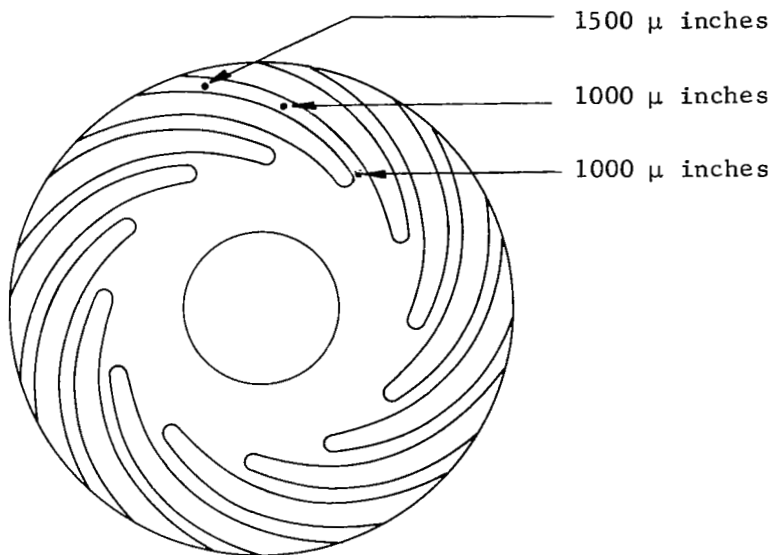


Fig. 33 Nickel-Chrome Groove Pattern on Rene 41 Thrust Bearing vs. $\text{BaF}_2/\text{CaF}_2$ Eutectic on Rene 41 Thrust Collar. After High Speed Rubs at 1400 F in Argon at 38,500 rpm.

APPENDIX A

TASK III. BEARING MATERIALS SCREENING STUDY

Purpose:

To select substrate materials and coatings for application to gas bearings operating in an inert gas atmosphere at temperatures of 900 F and 1400 F.

Scope (From Contract)

1. Concurrent with the initiation of Task I, a screening study of the literature and current related material programs shall be conducted to identify potentially useful structural substrate materials, solid lubricant surface coatings, and wear-resistant surface coatings for application to gas bearings operating in an inert gas atmosphere at temperatures of 900 F to 1400 F. The study shall include consideration of 4 materials being investigated under a NASA Contract.
2. At the conclusion of the study three (3) combinations of structural substrate material and surface coatings shall be selected for experimental evaluation at 900 F. Similarly, a second set of three (3) combinations of bearing material and surface coating shall be selected for experimental evaluation at 1400 F, making a total of six (6) different materials and six (6) coatings. The criteria for material and coating selection shall include:
 - a. Long-time dimensional stability at temperature
 - b. Surface integrity under momentary high-speed rubs
 - c. Ease and quality control of coating application
 - d. Adherence integrity at edges and other sharp changes in surface contour

The selected combinations shall be submitted to the NASA Project Manager with the screening study, together with supporting data justifying their selection for the respective temperature levels. This data shall be submitted in accordance with Article II, Period of Performance.

Recommendations for Bearing Combinations

For reasons which are discussed briefly on the following pages, the material combinations which were selected for Task IV, Experimental Evaluations of Bearing Materials were as follows:

900 F Operation

Bearing Material		Journal Material	
Substrate	Coating	Substrate	Coating
1. AISI 4340 Steel	Plasma-sprayed chrome oxide	AISI 4340 Steel	Plasma-sprayed chrome oxide*
2. A-286 Stainless	Flame-plated Al_2O_3	A-286 Stainless	Flame-plated cobalt bonded tungsten carbide*
3. Haynes 25	Flame-plated Al_2O_3 *	Haynes 25 Cobalt-worked to 40 Rc	none

1400 F Operation

Bearing Material		Journal Material	
Substrate	Coating	Substrate	Coating
1. TZM Molybdenum	Flame-plated Al_2O_3	TZM Molybdenum	Ni-Cr bonded chrome carbide*
2. TD Nickel	Flame-plated Al_2O_3	Haynes 25 Sol'n treated	Stellite 12*
3. Rene-41	None**	Rene 41	Fused eutectic film 40% CaF_2 /60% BaF_2

*In the thrust bearing tests, this coating was sprayed through a mask to form the grooves.

** In the thrust bearing tests, it was necessary to form a groove pattern on the Rene 41 by spraying on a nickel-chrome alloy on the surface through a mask.

A. Substrate Materials

In previous studies (A-1, A-2) which were done for Pratt and Whitney Aircraft under NAS-3-4179, type 416 stainless was used for the substrate material. At temperatures up to 500 F, this alloy was a reasonable choice because of strength, dimensional stability and ease of machining. However, for applications in the 900 F range, it is far from optimum and, at 1400 F, it is completely unsuitable. Therefore, a survey was made to determine which other alloys should be considered for high temperature operation. The obvious requirements for these materials were:

- Good high temperature strength
- High stress-rupture life
- Dimensional stability
- Potential for achieving 50,000 hour design life

Of these requirements, dimensional stability is certainly the area of greatest unknowns. References A-3 and A-4 present a review of the current state of the art. As noted in Reference A-3, there are two primary mechanisms which can cause dimensional instability. These are: metallurgical changes and relaxation of residual stresses. The former is normally resolved by proper heat treatment to achieve a material which is in a stable condition at the operating temperature of the component; the latter, by adequate stress relief after machining. In this application, particularly at 1400 F, we are in an area where many of the high strength alloys will age-harden. Over-aging and grain boundary migration in this temperature range could result in subtle dimensional changes occurring over a length of time. There is very little information available to show whether this is true or not.

At 900 F, the problems are much less critical since changes in metallurgical structure, if any, should be very small at this temperature.

A number of substrate materials were selected for consideration as bearing and shaft materials in both the 900 F and 1400 F range. These materials are listed in Tables A-1 to A-3 at the end of this section. The choices were based primarily on past experience and common knowledge, although certain alloys such as cold-worked Haynes 25 at 900 F were selected to evaluate a specific point. In that

case, it was the sliding behavior of the uncoated alloy which was the primary interest.

In the following paragraphs, the reasons for the final selections are discussed briefly.

1. Substrate Materials for 900 F

For 900 F, the following material candidates from Table A-1 were recommended for evaluation tests:

(a) AISI 4340

This is a low alloy steel with excellent strength and stress-rupture properties. It has been used by MII for a number of gas bearing applications. The alloy is readily available from a number of sources and the background on proper treatments and machining techniques is well established.

In order to achieve better dimensional stability, the heat treatment shown in Table A-1 was modified as follows:

Heat treat 1500-1550 F Oil Quench

Refrigerate to -100 F for one hour immediately after quenching

Temper at 1100 F for two hours. Cool.

Repeat refrigeration and temper cycles two more times.

(b) A-286 Stainless

This is a high temperature austenitic stainless for use where high corrosion resistance is essential. It has outstanding strength, is readily available and should be dimensionally stable in this temperature range with the heat treatment called out in Table A-1

(c) Haynes 25

This is a wrought, cobalt-base alloy with outstanding strength over a very wide temperature range. One reason for considering this alloy for this application is because it has been reported by Linde that Haynes 25 has good sliding characteristics when mated against flame-plated coatings.

This offers the possibility that the Haynes 25 could be used as the shaft material without any coating. Only the bearings would require coatings, thus minimizing the problem of quality assurance.

There is one qualification which should be made with regard to the use of uncoated Haynes 25 as a mating surface. That is, for best sliding compatibility, the Haynes 25 should be work-hardened to about 40-45 Rc. This does not present any obvious problems for 900 F operation. However, at about 1250 F, the cold-worked Haynes 25 recrystallizes and this would probably result in significant dimensional changes. This is the reason why uncoated Haynes 25 was not being considered for 1400 F tests. If it cannot be used in the cold-worked condition at 1400 F, then a coating would certainly be necessary to prevent surface damage.

2. Substrate Materials for 1400 F

As noted previously, dimensional stability could be a major problem in this temperature range.

The safest approach to this problem of dimensional stability would be to use metals with as low an alloy content as possible. A plain, very low carbon steel, completely annealed, would be an ideally stable material. A lack of high temperature strength rules out this approach for most metals. However, there are two particular candidates which could be considered for use at 1400 F because they fit in this category of low alloy content and yet have good strength characteristics. These candidates are: TD nickel and TZM molybdenum. In addition, one conventional high temperature superalloy, Rene 41, was selected as being typical of the age-hardenable alloys. The reasons for these selections are as follows:

(a) TD Nickel from DuPont

This material is 98% nickel with 2% thorium oxide uniformly dispersed as sub-micron particles throughout the structure. The thoria acts as a strengthening agent at high temperature. Since the thoria does not dissolve in, or react with, the nickel, even at the melting point of nickel, there are no metallurgical changes which would be of concern.

The only heat treatment required is a stress relief. The material has only moderate strength at low temperatures, but maintains this strength over a very wide temperature range. At 1800 F, it is comparable to the best of the nickel or cobalt based superalloys. In addition, the TD nickel has very high thermal conductivity, close to pure nickel.

Discussions with metallurgists who are familiar with this material indicated that the TD nickel was an excellent choice for the bearings and the support structure, but questionable for high speed rotating components (A-5). The strength of the material was not considered to be consistent enough for high reliability. Nevertheless, since TD nickel does have a major advantage from a standpoint of dimensional stability, and since the dispersion-strengthened alloys will be increasingly important in high temperature materials technology, it is still considered to be a good candidate for evaluation. It was recommended that the TD nickel be used for the bearing material and that the shaft material be solution-treated Haynes 25. The Haynes 25 has a coefficient of thermal expansion which is very close to the TD nickel. By using the Haynes 25 in the solution-treated condition, the problem of metallurgical transformation should be minimized. This will also provide an opportunity to get actual measurements on dimensional changes if these do occur. Any data which can be obtained on the use of Haynes 25 at 1400 F would be very useful since this alloy has outstanding high temperature strength.

(b) TZM Molybdenum from Climax Molybdenum

This is a molybdenum base alloy which is 99.4% Mo with 0.5% Ti and .08% Zr. It has outstanding strength, particularly at high temperatures. Because of the low alloying element content, the material should have good dimensional stability. The only heat treatment required is a stress relief.

On the negative side, it should be noted that TZM is expensive, difficult to machine, and has poor ductility, particularly at low temperatures. It oxidizes at a catastrophic rate above 1300 F in air. In

spite of these disadvantages TZM has been used successfully in high temperature gas bearings and it represents one of the best high temperature materials as far as strength and stability are concerned. For these tests, it was proposed that the TZM be used as the substrate material for both the shaft and the bearings.

(c) Rene 41

This alloy has good high temperature strength, and is typical of the age-hardenable nickel-base alloys such as Waspalloy, Udimet 700, etc. One of the goals of these tests was to determine, at least for short periods of time, how well this class of alloys can be expected to hold dimensions. It was proposed that the Rene 41 be used as the substrate material for both the shaft and the bearings.

Foil Materials

At this time, three materials are considered promising for use as conformable bearings materials. These are:

Molybdenum

Tantalum

Tungsten

Foil is available in a variety of thicknesses ranging from .0005" up to at least .010". As shown in Table 3, these metals have good high temperature strength. In addition, both molybdenum and tungsten should provide good substrate materials for solid lubricant coatings. These foils could be used at both 900 F and 1400 F as long as air was excluded.

An attempt was made to locate sources for foils made of alloys of these metals, such as TZM molybdenum, since the alloy would have better strength at temperature. Climax Molybdenum could supply TZM rolled to .008" thick foil, but this seems to be too stiff for conformable bearing applications. They were hesitant about further mechanical reduction in thickness because of a loss in strength. However, it is possible to chem-mill the foil to about .005".

B. Coatings

Background

Flame or plasma-sprayed coatings have been used successfully in a wide variety of applications, such as for thermal barrier coatings or for wear-resistant or friction-modifying surfaces. Quoting from Ref. A-6, "The combination of two materials, as a coating and substrate that results in a materials system possessing useful (and frequently superior) properties, has almost unlimited potential". Yet, there is surprisingly little effort being made to determine how or why these coatings adhere to a substrate, or what guidelines are available for the selection of coatings for abrasive resistance. References A-6 and A-7 present the most up to date background information. Good technical bulletins are available from commercial sources (Ref. A-8) on the procedures required for grinding and finishing these coatings. This is just as important, if not more so, than the development of good procedures for applying the coatings. Improper grinding can weaken even the most adherent coating. Reference A-9 presents a summary of test data which one supplier has obtained on the sliding behavior of a number of coating material combinations.

There is a general agreement among competent investigators that the bond between the sprayed coating and the substrate is not simply a mechanical bond, although the strength of the bond is increased significantly by roughening the surfaces (Ref. A-10). Even this operation has many subtle aspects. For example, it has been found that substrate materials, grit-blasted with fresh Al_2O_3 particles, will give a much more adherent coating than materials which were grit-blasted with used Al_2O_3 . The fresh particles have sharper edges and a larger particle size. As the grit is used, the average particle size decreases, because of fracture, and the edges become rounded. This results in a significant loss in coating adherence.

Some form of solid state diffusion bonding mechanism must also be involved, otherwise it would be difficult to account for the cohesive as well as the adhesive strength of the coatings. However, since the composition of the coating material can vary from straight ceramic powders (e.g. Cr_2O_3 or Al_2O_3), through metal bonded cermets (e.g. cobalt bonded WC or Ni-Cr bonded Cr_3C_2) to all

metallic coatings (e.g. W or Mo), it is apparent that several mechanisms may be involved, depending on the actual composition of the coating and of the substrate material. Grisaffe and Spitzig (Ref. A-6 Page 169) found that plasma-sprayed tungsten particles on a polished 304 stainless substrate formed an interface alloy, apparently by rapid solid-state interdiffusion. A similar bonding mechanism could occur when a metal bonded cermet was sprayed on a suitable metallic substrate. In that case, some of the metal binder could interact with the substrate to form a more adherent bond. This also suggests that it might be worthwhile to sinter the coating after it had sprayed, thus improving the interface bond. This procedure is actually used with "self-fluxing" alloys (Ref. A-7, Page 85), and in at least one case it is known that the density and adherence of a metal bonded carbide coating was improved by sintering (A-11).

The adherence of the coatings also depends to a large extent on the techniques used to spray the materials. This can be covered to some extent by specifications, and would certainly be improved if we had a better understanding of the processes involved. However, in the last analysis, the real key to the problem would be the development of a non-destructive qualification test for coating integrity. This could be used to evaluate the end product and would eliminate the need for detailed specifications on processing techniques.

Edges present a real problem as far as coating adherence is concerned. It is standard practice to break all sharp edges with a .015 inch radius to minimize chipping or spalling. Experience has shown that the use of an undercoat such as molybdenum or nickel-chrome will give better edge finishes. When a groove pattern is sprayed on top of a flat surface, the edges of the grooves are tapered rather than sharp and square. This is the result of geometrical factors in making the masks and in spraying the grooves. Both processes lead to the formation of a tapered edge which is less susceptible to damage. A photograph of a typical groove edge is shown in Fig. A-1.

There is no information available in the literature or in trade sources as to the effect of time at temperature on the bond strength of the coatings. Finally, although a number of techniques have been suggested for the non-destructive evaluation of the integrity of the coatings, none of these have been developed to the

point where they can be used as a standard evaluation technique.

Selection of Coatings

There are a number of criteria which have been suggested to select coatings for sliding applications. These include.

High Hardness

Low coefficient of friction (solid lubricant films)

Non-metallic surfaces

In previous NASA studies (A-1, A-2) the following coatings or material combinations were evaluated in both low speed start-stop tests and during high speed rubs

<u>Combination</u>	<u>Category</u>
1. Chrome oxide coating on pad bearing vs. Chrome oxide coating on journal	Hard, non-metallic surfaces
2. Ni-bonded WC coating on pad vs Al_2O_3 coating on journal	Hard surfaces Have been used in gas bearing gyros
3. Through-hardened M-50 tool steel pad vs. Co-bonded WC coating on journal	Hard surfaces
4. Resin bonded MoS_2 lubricant film on pad vs. hardened 416 stainless journal	Solid lubricant film
5. DU [*] surface on pad vs molybdenum coated journal	Self-lubricating low friction material

* Spherical bronze particles sintered to steel backing and impregnated with Teflon and lead

Of these combinations, the self-mated chrome oxide was particularly promising under both start-stop and high speed rub conditions. The nickel bonded carbide mated against the Al_2O_3 coated shaft was an excellent combination for start-stop low speed sliding contacts, but deteriorated rapidly during high speed rubs because of metal transfer and subsequent abrasion. The through-hardened M-50 tool steel bearing against the carbide-coated journal showed very limited damage resistance at low speeds, and gave very poor results at high speeds.

Of the low friction coatings, the resin-bonded MoS_2 solid lubricant film gave encouraging results, but the wear life of the film was the limiting item, especially at high speeds. The DU material, which should also be considered as a solid lubricant film, was very effective during high speed rubs, but showed limited load carrying capability as far as hydrodynamic performance was concerned. It was hypothesized that this material was porous enough to permit gas leakage out of the high pressure region.

From these results, it is apparent that hardness is too vague a term to be used as an effective criterion for material selection. It is true that hard surfaces are generally more damage resistant, but many hard combinations can give very poor results.

The low friction coatings (solid lubricant films) have shown considerable promise, although the wear life of the films is the governing factor. Possibly, the combination of a very thin solid lubricant film on top of a good, wear-resistant coating would be the ideal solution to the sliding problem.

As far as non-metallic surfaces are concerned, the results described above had indicated that when metals or metal binders were present in the surface, transfer and scoring would be observed. This was not too surprising since the sliding velocity during a high speed rub was about 400 feet per second under shock loads as high as 100 g's. Even in a small fraction of a second, frictional heat generation would be extremely high. Therefore, it could be argued that self-bonded ceramic coating should have better sliding behavior since there would be much less tendency for welding and material transfer. The results obtained with the self-bonded chrome oxide seemed to bear out this conclusion.

However, further study of these test results also showed that most of the damage always took place on the bearing pads, rather than on the journal surfaces. This was true, even with the self-mated chrome oxide. Since only one area of the pad bearing was in contact during a high speed rub, while the contact area on the shaft was continually changing, it seemed reasonable to expect more damage to the pad bearing. This brings up the question of the effect of the importance of the relative positions of the coatings on these test results. For example, these two combinations had been evaluated in the previous tests:

<u>Pad Material</u>	<u>Journal Material</u>
Nickel-bonded tungsten carbide coating	Al ₂ O ₃ coating
Through-hardened M-50 tool steel	Cobalt-bonded tungsten carbide coating

In both cases, the coating on the pad had a more predominantly metallic character. Failure was the result of metal being transferred from the pad to the shaft, and subsequent scoring of the pad.

To determine the effect of reversing the position of the coatings on these results, some tests have been run by MTI under a current Air Force Contract (A-13). Stop-start tests were made in air at 1400 F, using the following combinations.

<u>Pad Material</u>	<u>Journal Material</u>
1. Nickel-chrome bonded chrome carbide	Al ₂ O ₃ coating
2. Al ₂ O ₃ coating	Nickel-chrome bonded chrome carbide coating

The first combination showed poor results. Heavy material transfer took place from the pad to the journal. However, when the combination was reversed, excellent results were obtained. The surfaces were highly polished, and no damage or transfer was observed. Although these results were not high speed tests, they certainly show that the relative positions of the coatings can be important. This has been factored into the final selection of material combinations for the evaluation tests.

In the following paragraphs, the reasons for the specific choices of coatings are described briefly.

Coating Material Combinations for 900 F

(a) Chrome oxide on 4340 steel pad vs Chrome oxide on 4340 steel journal

Because the chrome oxide coating was the best material found in the 500 F tests, it must also be considered as the leading candidate for 900 F operation. However, it should be noted that the limit of usefulness of this coating is about 1000 F. Above this temperature, the chrome oxide deteriorates in bond strength. The 4340 steel was selected as the substrate material because it has been used before with chrome oxide and has given satisfactory results.

(b) Flame-plated Al_2O_3 on A-286 stainless pad vs flame-plated cobalt bonded WC on A-286 stainless journal.

This coating combination gave very promising results in previous work, as far as the start-stop results were concerned. However, problems were encountered because of metal transfer during high speed rubs. This time, the relative positions of the coatings has been reversed so that the metal-bonded carbide is on the journal and in non-metallic Al_2O_3 coating is on the bearing. If the results of the Air Force tests are correct, then these materials should be much more effective when used in this manner.

(c) Flame-plated Al_2O_3 on Haynes 25 pad vs Uncoated, cold-worked Haynes 25 journal

The purpose of this test is to determine if the cold-worked Haynes 25 is a good mating material for running against a coating. This would simplify many design and quality control problems. Again, the relative position of the coatings has been set so that the metallic surface is on the journal and the non-metallic coating is on the bearing.

Coating Material Combinations for 1400 F

(a) Flame-plated Al_2O_3 on TZM pad vs nickel-chrome bonded chrome carbide on TZM journal.

Preliminary results, which have been obtained on the Air Force program at 1400 F in the air, have shown that this is a very promising combination of coatings for

resistance to sliding damage. There is a question as to how well this combination will run in an inert atmosphere where no oxide films would be formed, but this can only be resolved by experimental evaluations.

(b) Flame-plated Al_2O_3 on TD nickel pad vs Sprayed Stellite 6 coating on Haynes 25

This combination was selected as another approach to the idea of using a metallic coating for the journal and a non-metallic coating for the bearing. If good sliding behavior is obtained with this coating combination, it opens up a number of possibilities for simplifying the quality control problems on these coatings since the Stellite coatings can be applied by a variety of well established techniques. Again, the performance of these materials in an inert atmosphere may not be as good as in air but the fact that Stellite is effective in liquid metal bearings (A-14) makes this approach look worthwhile.

(c) Fused Eutectic CaF_2/BaF_2 solid lubricant film on Rene 41 pad vs same film on Rene 41 journal.

This is one of the very few solid lubricant films capable of being used at high temperatures (A-15). At the present time, it is recommended that this coating be applied directly to the Rene 41 substrates. If the evaluations indicate that the coating is promising, but lacks adequate wear life, then consideration can be given to means for applying the coating to a substrate material or over another more wear-resistant coating in order to improve life.

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TABLE A-1

MATERIALS UNDER CONSIDERATION AT 900°F

Material	Chemical Analysis									Modulus of Elasticity psi x 10 ⁶	Density lb/cu.in.	Tensile Temp.	Strength 1000 psi	0.2% yield 1000 psi	Heat Treatment	Stress - Rupture Life			Thermal Expansion in/in/°F x 10 ⁶ Temp.Range
	C	Al	Ti	Mo	Cr	Co	Fe	Ni	Other							Temp.	Hours	1000 psi	
Unitemp 14 MV AMS 6302 (Iron base)	.3			.5	1.25	-	R		Mn .55 Si .65 V .25 S .04 P .04	70°F - 30.5 1000F 25.0	.283	1000°F	108.0	92.0	Harden - 1550 - 1650°F O.Q. Temper-1100°F	1000°F	10,000	31.0	70-1200°F 8.1
A-286 (Iron base)	.08	.35	2.0	1.25	15.0	-	R	26.0	Si .7 Mn 1.5 V .25	70°F - 29.0 1000F - 23.5	.286	1000°F	131.0	87.5	Sol Treat - 1800°F 1 Hr.O.Q. Age - 16 hrs. 1325°F AC	1000°F	1,000	88.0	80-1000°F 9.78
AISI 4340 (Iron base)	.4	-	-	.25	.8	-	R	1.85	Si .25 S .03 Mn .7 P .03	70°F - 29.3	.283	900°F	125.0	115.0	Harden - 1475 - 1550°F O.Q. Temper 1050°F AC	900°F	1,000	50.0	0-1200°F 8.1
416 S.S. (Iron base)	.15	-	-	0.6	13.0	-	R	-	S .15 Si 1.0 Zr .6 Mn 1.25 P .06	70°F - 28.0	.278	900°F	48.0	35.0	Harden - 1700F- 1830°F O.Q. Temper-1200°F AC	900°F	10,000	33.0	0-1000°F 6.7
Rem-Cru Al10 AT (Titanium base)		5	R						Sn 2.5	70°F - 17.0	.161	1000°F	75.0	58.0	Stress Relieve 1000-1200 F	1000°F	1,000	20.0	0-1200°F 5.5
Haynes 25 (Cobalt base)	.10				20.0	R	3.0	10.0	W 15.0 Mn 1.5 Si 1.0	70°F - 35.0 1000°F - 28.3	.333	1000°F	82.2	37.6	Sol - 2200°F A.C.	1350°F	1,000	30.25	70-1000°F 8.3

TABLE A-2

MATERIALS UNDER CONSIDERATION FOR 1400°F

Material	Chemical Analysis										Modulus of Elasticity psi x 10 ⁶	Density lb/cu. in.	Tensile Temp.	Strength 1000 psi	0.2% yield 1000 psi	Heat Treatment	Stress - Rupture Life			Thermal Expansion in/in/°F x 10 ⁻⁶ Temp. Range
	C	Al	Ti	Mo	Cr	Co	Fe	B	Ni	Other							Temp.	Hours	1000psi	
M-252 (Nickel- base)	.15	.1	2.5	10.0	19.0	10.0	5.0	.005	R	-	70°F - 29.8 1500F - 21.8	.298	1400°F	137	104	Sol-1950°F 4hrs AC Age-1400°F 15hrs AC	1400°F	10,000	14.0	70°-1500°F 7.8
U-700 (Nickel base)	.15	4.5	3.5	5.25	15.0	17.0	4.0	.025	R	-	70°F - 32 1500F - 22.5	.286	1400°F	150	120	Sol-2150°F 4hrs.AC Age-1975°F 4hrs.AC Stab-1550°F 24hrsAC FinAge1400°F16hrsAC	1400°F	700	65.0	70°-1800°F 7.7
U-500 (Nickel base)	.15	3.0	2.75	4.0	18.0	17.0	4.0	.01	R	Mn .75 Si .75 Cu .15 S .015	70°F - 33 1500F - 24.5	.290	1400°F	155	-	Sol-2150°F 2hrs.AC Age-1975°F 4hrs.AC Stab-1550°F 24hrsAC Fin Age-1400°F 16 hrs AC	1500°F	10,000	17.5	70°-1800°F 7.7
Waspaloy (Nickel base)	.10	1.3	3.0	4.5	20.0	13.5	2.0	.008	R	Si .75 Mn .75 Cu .5 Zr .06 S .3	70°F - 30.6 1800F - 21.1	.296	1400°F	117.0	99.0	For Rupture Prop. Sol-1975°F 4hrs.AC Age-1550°F 24hrs AC Fin Age-1400°F 16hrs. AC	1500°F	10,000	17.5	70°-1800°F 7.7
S-816 (Cobalt base)	.38	-	-	4.0	20.0	44.0	5.0	-	20	Cb+Ta 4.0 W 4.0 Si .9 Mn 1.8	70°F - 35.2 1500F - 25.4	0.313	1500°F	73	-	Sol-2150-2250°F 1 hr. W.Q. Age-1400-1500°F 12-16 hrs. AC	1350°F	10,000	21.0	70°-1400°F 7.7
Rene 41 (Nickel base)	.13	1.6	3.15	19.0	11.0	10.0	5.0	.007	R	Si .2 Mn .1 S .015	70°F - 30.5 1600F - 23.2	.298	1400°F	136.0	107	For Rupture Prop. Sol-2150°F 2hrs.AC Age-1650°F 4hrs.AC	1500°F	1,000	28.0	70°-1500°F 8.4
TZM (Molybdenum base)	.03		.48	99.40						Zr .08 N ₂ .002 H ₂ .0005 O ₂ .0025	70°F - 46 2000F - 29	.369	1600°F	108	95	Stress Relieve 2100°F	2000°F	100	52.0	70°-212°F 3.0
TD Nickel (Nickel base)									98.0	ThO ₂ 2.0	70°F - 30	.322	1400°F	28	26	Stress Relieve 1800F to 2000F 15 minutes	1400°F	1,000	16	70°-1000°F 8.5

TABLE A-3 Candidate Foil Materials

Foil Materials	Modulus of Elasticity psi x 10 ⁶	Tensile Stength psi x 10 ³	Yield Strength psi x 10 ³
Tantalum	70 F 27 1600 F 26	70 F 60 1600 F 30	70 F 48 1600 F 15
Tungsten	70 F 59 1600 F 55	70 F 220 1600 F 66	70 F 220 1600 F 15
Molybdenum	70 F 47 1600 F 33	70 F 95 1600 F 50	70 F 82 1600 F 30



Fig. A-1 Overall View of Groove Pattern and Close-up Showing Groove Detail. Grooves Formed by Plasma-Spraying Cr_2O_3 Through a Metal Mask.

APPENDIX B

PREPARATION OF TEST SPECIMENS AND DIMENSIONAL STABILITY TEST RESULTS

1. Substrate Materials

All of the substrate alloys used in this work were purchased with a Certification of Material Composition. The suppliers are listed in Table B-1.

The base materials were rough-machined to shape, heat-treated by the producers listed in Table B-1, and then finish ground to size. Certifications of the heat-treating procedures were also obtained.

2. Coatings

With the exception of the eutectic fluoride film and the Stellite 6, all coatings were done in accordance with MTI specification number 29, a copy of which is included in this section.

The eutectic fluoride film was applied through the courtesy of Mr. Harold Sliney of the NASA Lewis Research Center. This was a eutectic composition of nominal composition 40% BaF_2 , 60% CaF_2 . The procedure for applying and fusing this coating is described in Ref. B-1. The Stellite 6 was applied at the Linde Flame-Plating Development Laboratory in Speedway, Indiana. An arc torch was used.

The journals, tilting pad bearings and thrust collars were all sprayed with coatings 0.007-0.010" thick (except for the fluoride eutectic film) and were then ground and lapped to a finished thickness of 0.003". The grooved thrust bearing patterns were applied by grit-blasting the entire bearing surface, then securing a hardened 302 stainless steel template on the bearing surface and spraying a coating 0.004 to 0.006" thick through the template. These templates had been photoetched to form a negative of the groove pattern. The areas which were open to the spray thus formed the lands and the masked areas formed the grooves. Figure B-1 shows a typical bearing pattern, the template,

and the template holder. After spraying, the template was removed and the sprayed coating was ground and lapped until the desired groove depth had been achieved.

The fluoride eutectic film was applied to give a coating thickness of 0.001-0.0015". The fused coating was finished by machining the surface with a single point carbide tool. Some difficulty was encountered in getting a uniform thickness on the surfaces. It is very probable that the Rene 41 parts warped slightly during the fusing cycle. This is a practical manufacturing problem which must be overcome if this type of coating is to be used.

3. Bond Strength Tensile Tests

As stipulated in MTI specification 29, tensile test specimens of the various materials were coated at the same time that the bearing parts were being sprayed. These tensile test pieces were used to measure the bond strength of the coatings as described in the specification. The results are given in Table B-2. These values are typical of the bond strengths that MTI has been obtaining on various coated parts.

4. Dimensional Stability Tests

Although a detailed study of the dimensional stability of substrate materials was beyond the scope of this contract, some preliminary tests were made to establish some idea of the magnitude of the stability problem. Dummy test shafts 0.75" in diameter by 3" long were made of each of the substrate alloys. These shafts were heat-treated and finish ground at the same time and by the same procedures as was used for the test specimens. The diameters of the test shafts were then carefully measured with a Cleveland Instruments INDI-ACT gage to within 25 microinches. These measurements were made in a clean, air-conditioned test facility. All specimen handling was done using plastic gloves. These shafts were heated in an argon-blanketed, stainless steel pot for 100 hours at 900 F or 1400 F, depending on the test temperature at which they were to be evaluated in the bearing test. They were then furnace cooled and remeasured. The results are shown in Table B-3.

Of these alloys, only the TD nickel looked promising. Metallurgical sections were also prepared to determine the structures of these alloys before and after these tests. Photomicrographs of these structures are shown in Figs. B-2 to B-8.

The following comments were made by Professor N. Stoloff of RPI who was acting as a consultant on this project.

Rene-41 is a nickel-base alloy which normally contains about 0.08% carbon, as well as about 19% Cr, 11% Co, 9% Mo, 3% Ti and 1.5% Al. Therefore there is opportunity for both carbide formation as well as γ' (Ni_3Al) during exposure. The fact that the dimensional change on this alloy was so small indicates either that (a) carbides and γ' produce opposite effects on the lattice parameter or (b) that at 1400 F no further precipitation occurs, due to pretreatment at 1450 F for 4 hours. From the microstructure it appears that further precipitation did occur and explanation (a) appears the most likely. Incidentally, at normal carbon contents, both TiC and M_6C should be present.

The stability of TD nickel is to be expected on the basis of the stability of the oxide dispersion.

The relatively good performance of 4340 steel is somewhat surprising, in view of its high carbon content. The microstructures showed no visible difference due to exposure, but the carbides are so closely spaced that it would be difficult to detect differences. At higher temperatures 4340 would probably show much more drastic changes.

The poor behavior of TZM molybdenum could arise from factors other than precipitation. These are inadequate stress relief, or the formation of an oxide film due to impurities in the inert gas atmosphere. Further exposure runs on this alloy would be desirable so that various pre-treatments could be employed.

Comparing the various alloys there is no obvious relation between fine initial grain size and dimensional changes in these experiments. In general, the dimensional changes do not correlate well with visible changes in microstructure.

For example, A286 stainless steel revealed no obvious further precipitation and performed badly, while annealed Haynes 25 did reveal additional precipitation with a large dimensional change. More sensitive techniques, such as electron microscopy or precision lattice parameters measurements, are required to determine accurately the structural changes that occur.

Ref. B-1 Sliney, H.E., Strom, T.N. and Allen, G.P., "Fused Fluoride Coatings as Solid Lubricants in Liquid Sodium, Hydrogen, Vacuum, and Air," NASA TN D-2348 Aug. 1964.

TABLE B-1 TEST MATERIALS
SOURCE AND HEAT TREATMENTS

<u>Substrate Material</u>	<u>Supplier</u>	<u>Heat Treatment</u>
4340 steel Cold-drawn annealed	Bowsteel Corp. Linden, N.J.	Harden 1500-1550 F O.Q. Refrigerate to -100°F for 1 hr. Temper 1100 F 2 hrs. A.C. Repeat refrigeration & temper cycles 2 times.
A-286 stainless	Advanced Alloys	Sol. 1800 F 1 hr. O.Q. Age 1325 F 16 hrs. A.C.
Haynes 25 (solution- treated)	Haynes-Stellite	Sol. 2200 F. A.C.
Haynes 25 (cold- worked)	Haynes-Stellite Forged by Monroe Forgings, Inc.	Cold reduced 15% no heat treatment
Rene 41	Forged by Monroe Forgings Inc.	Sol. 2150 F 2hrs. A.C. Age 1650 F 4 hrs. A.C.
TD nickel	DuPont	Stress Relieve 1800 F to 2000 F for 15 min.
TZM Molybdenum	Climax-Molybd. Co.	Stress relieve at 2100 F

TABLE B-2 TENSILE TEST RESULTS
ON COATING BOND STRENGTHS

<u>Substrate Material</u>	<u>Coating</u>	<u>Bond Strength</u>
4340 Steel	Chrome Oxide	4350 psi
A-286 Stainless	Al_2O_3	6970 psi
A-286 Stainless	Cobalt bonded tungsten carbide	6250 psi
Haynes 25 (solution treated)	Al_2O_3	3820 psi
Haynes 25 (solution treated)	Stellite 6	5990 psi
TZM Molybdenum	Nickel-chrome bonded chrome carbide	6570 psi
TZM Molybdenum	Al_2O_3	4480 psi
TD Nickel	Al_2O_3	4510 psi

TABLE B-3 SUMMARY OF EXPOSURE DATA

<u>Material</u>	<u>Diametral-Change</u> <u>Microinch/inch</u>	<u>Microstructures</u>	
		<u>As Received</u>	<u>Post-exposure</u>
TD Nickel	- 40	very fine grain structure some inclusions	slight grain growth
Rene 41	+ 78	grain boundary precipitation stringers, coarse grain structure	stringers appear to have spheroidized.
4340 Steel	-120	distinct fine and coarse carbides	no visible change
A-286 Stainless	-291	coarse grain structure inclusions, second phase.	no visible change.
Haynes 25 cold worked	-330		grain boundary voids, second phase
TZM Molybdenum	-400	cold worked	no visible change
Haynes 25 Soln. Treat.	-450	grain boundary voids	distinct additional precipitation particularly at grain boundaries

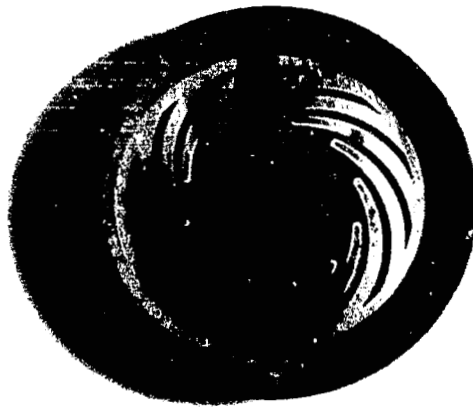
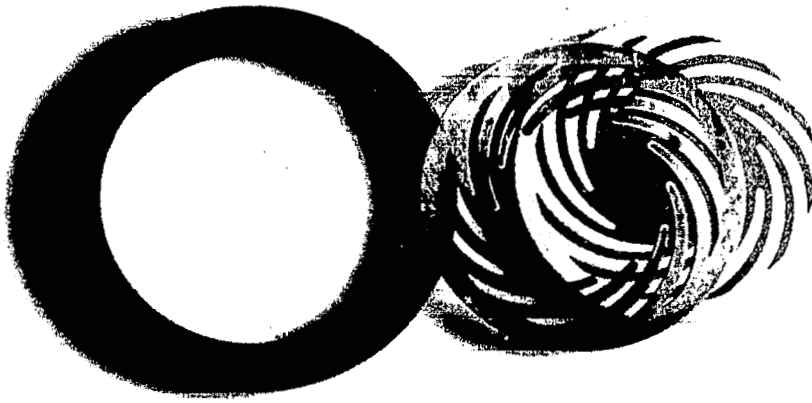
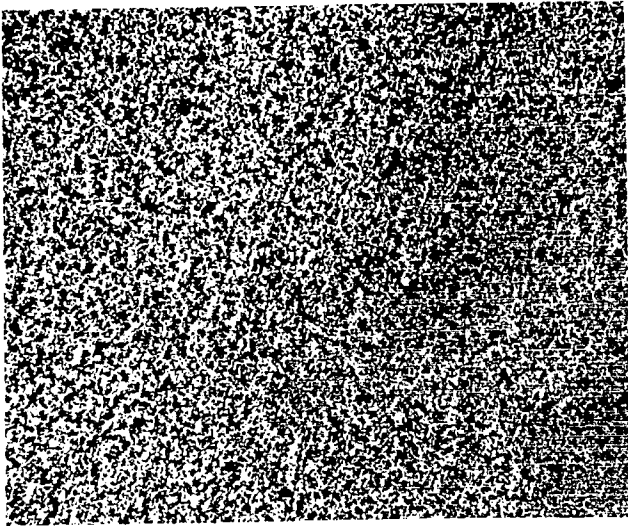
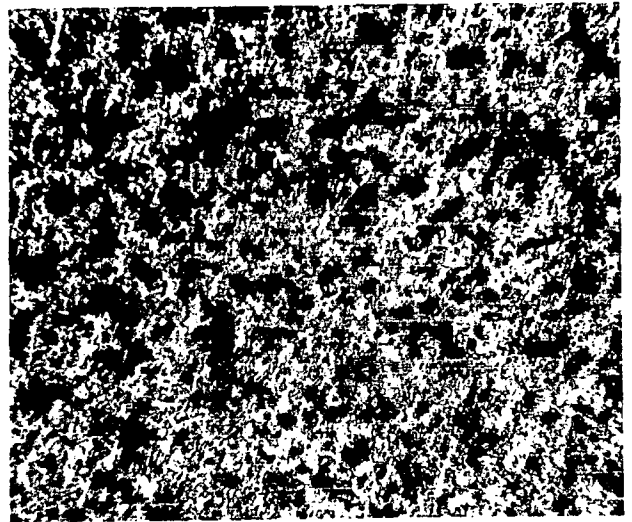


Fig. B-1 Set-up Used for Spraying Groove Patterns

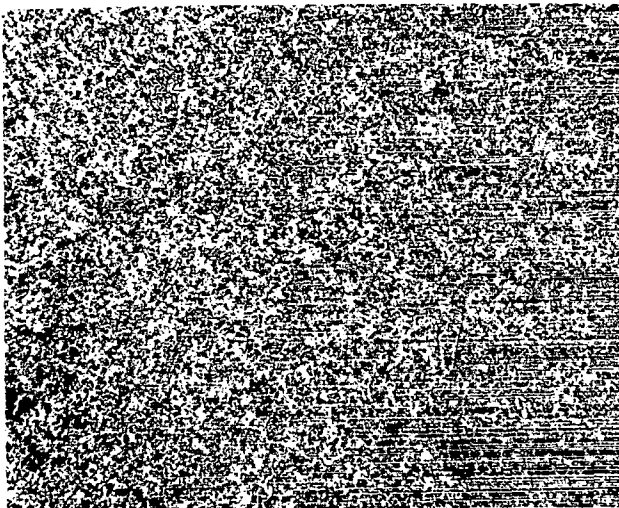


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500X

BEFORE TEST



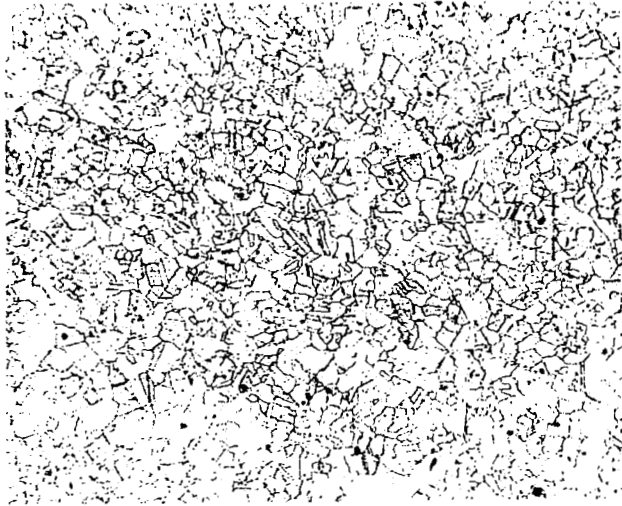
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500X

AFTER TEST

Fig. B-2 Microstructure of AISI 4340 Steel
Before and After 100 Hours at 900 F.

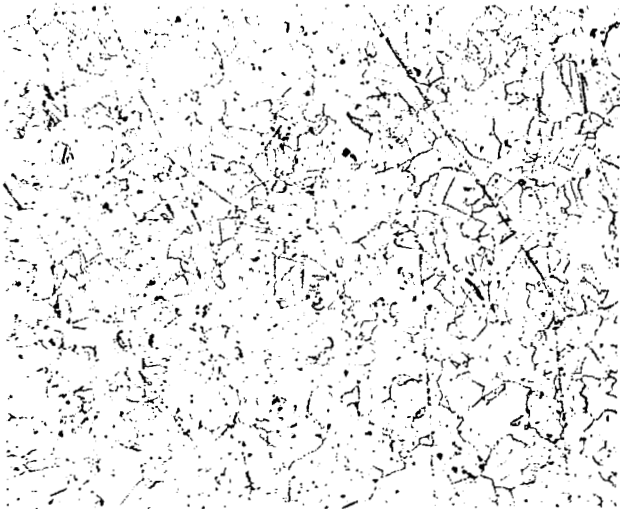


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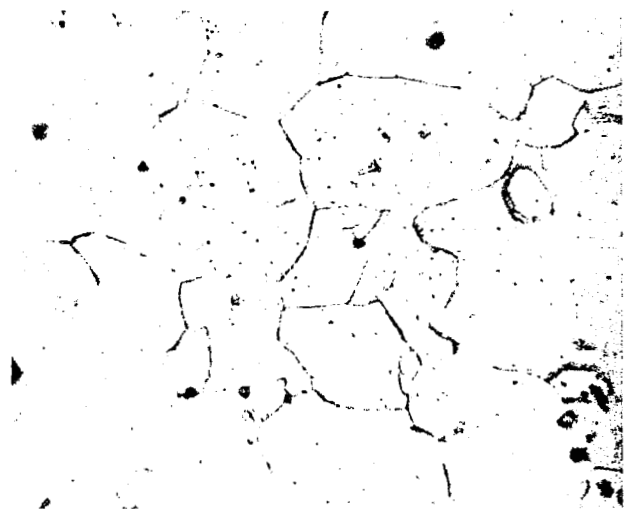


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BEFORE TEST



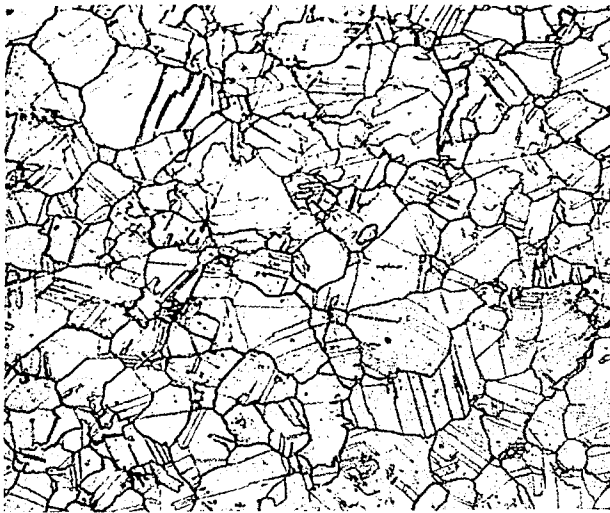
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500X

AFTER TEST

Fig. B-3 Microstructure of A-286 Stainless
Before and After 100 Hours at 900 F.

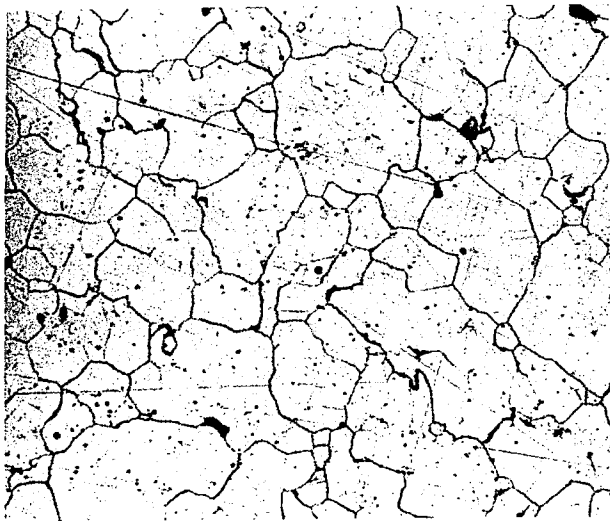


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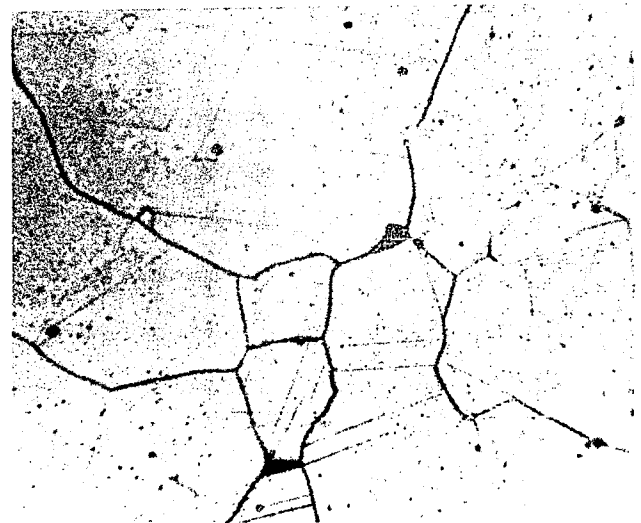


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AFTER TEST



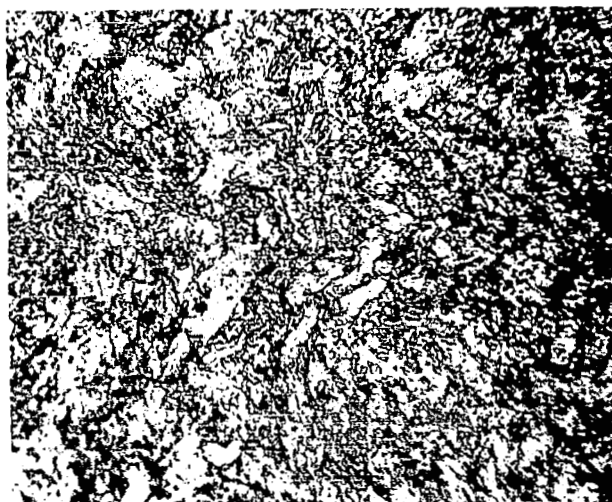
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Fig. B-4 Microstructure of Cold-Worked Haynes 25
Before and After 100 Hours at 900 F.



100X

BEFORE TEST



500X



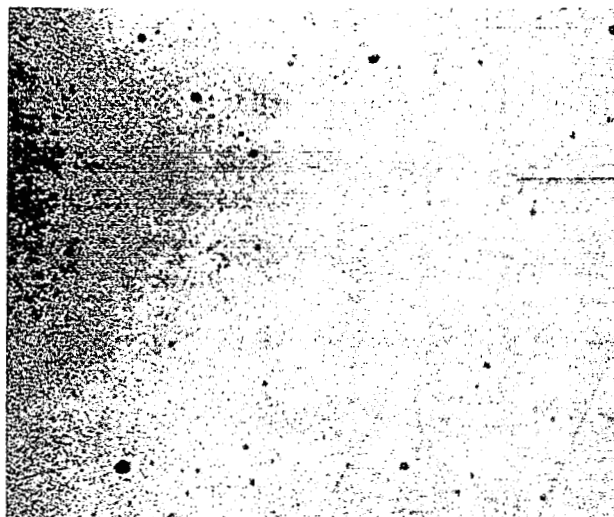
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AFTER TEST



500X

Fig. B-5 Microstructure of TzM Molybdenum
Before and After 100 Hours at 900 F.

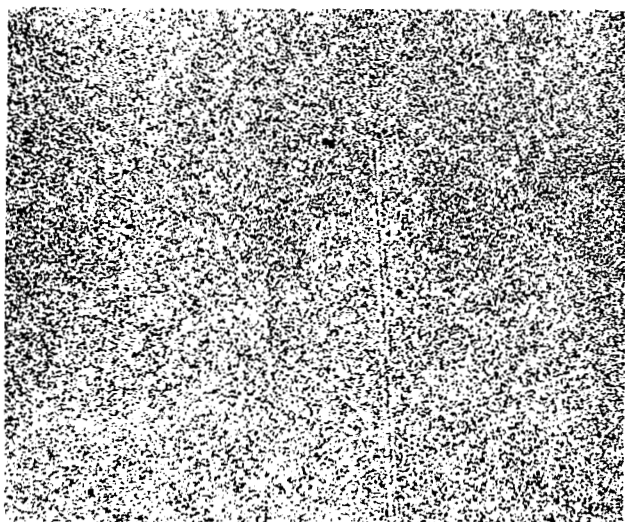


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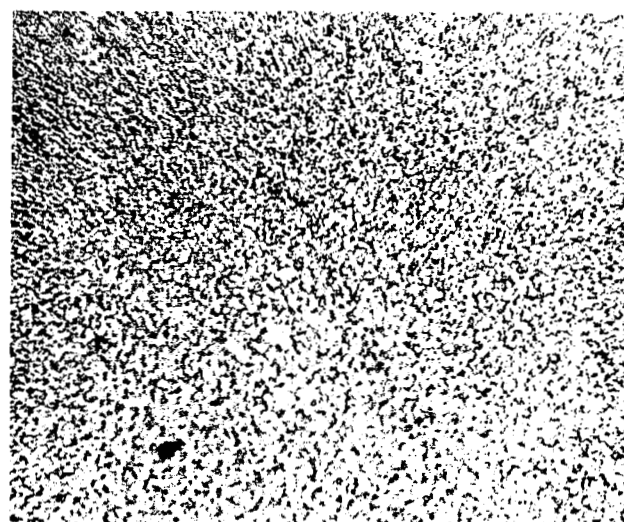


500X



100X

AFTER TEST



500X

Fig. B-6 Microstructure of TD Nickel
Before and After 100 Hours at 1400 F.

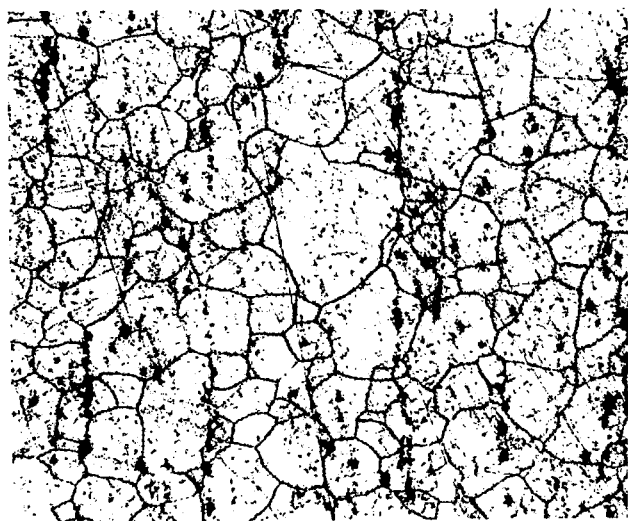


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BEFORE TEST

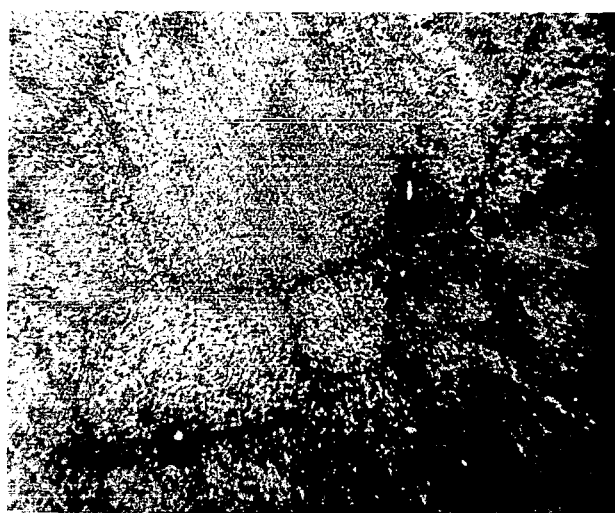


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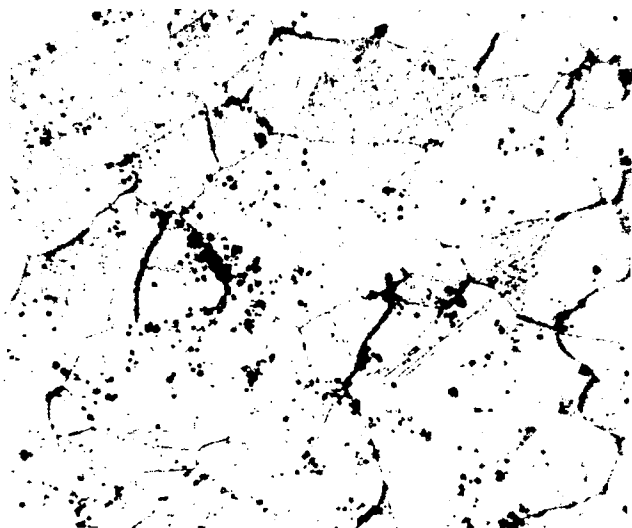
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AFTER TEST



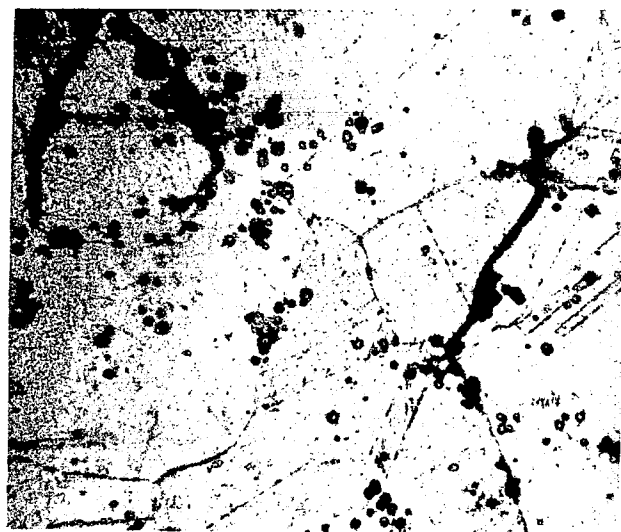
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Fig. B-7 Microstructure of Rene 41
Before and After 100 Hours at 1400 F.

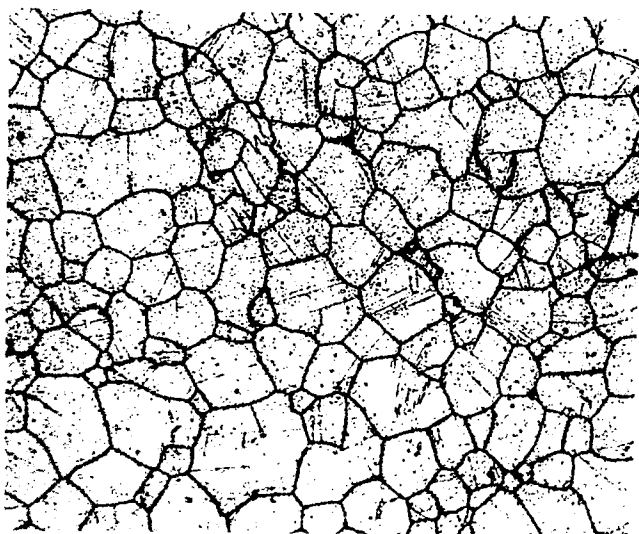


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BEFORE TEST

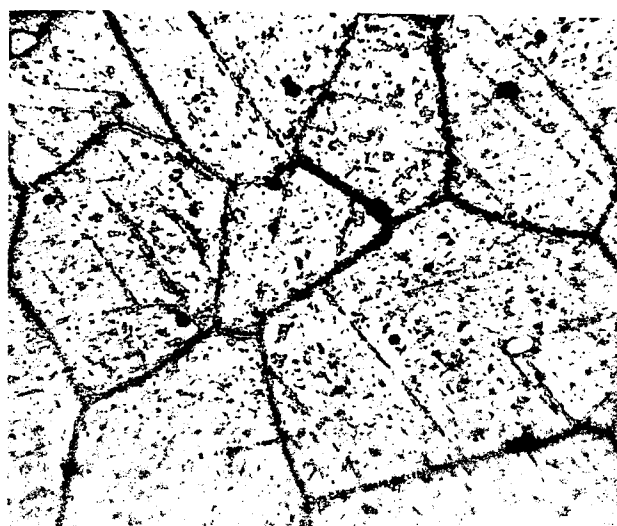


500X



100X

AFTER TEST



500X

Fig. B-8 Microstructure of Solution Treated Haynes 25
Before and After 100 Hours at 1400 F.

MTI SPECIFICATION #29

APPLICATION OF CERAMIC AND CERMET COATINGS TO THE SURFACES OF
BEARINGS AND SHAFTS

Issued: October 11, 1966

Revised: February 20, 1968

1. ACKNOWLEDGMENT Vendor shall mention this specification number and its revision number in all quotations and when acknowledging purchase orders.
2. PURPOSE To provide a procedure for the application of a surface layer of a hard, wear-resistant coating to bearing parts. Also to provide a procedure for the application of an undercoating (prior to application of the final coating) for the purposes of improving coating adhesion, or for providing the base material with improved corrosion resistance.
3. EQUIPMENT A specially constructed torch or gun which imparts an extremely high velocity and high temperature of a suitable carrier gas in which the powdered coating material is suspended. The carrier gas used shall be argon, unless otherwise specified.
4. PROCESS Two suitable processes for the satisfactory deposition of these hard coatings have been developed by vendors. These processes are generally described as the 'plasma flame spray' process and the 'detonation' process. Either process may be used unless the detail drawing of the part states otherwise.
5. COATING AND UNDERCOATING MATERIALS Shall be indicated on the detail drawing by name, e.g., chrome oxide coating, nickel or nickel-chrome or molybdenum undercoating. The identity of the materials shall be determined by the vendors powder or coating number.

The minimum bond strength between the final coating and the base material or between the final coating, the undercoating and the base material shall be 2000 PSI as determined by the bond strength test (Para.11)

6. BASE MATERIAL Prior to coating the parts should be, as far as is possible, in the finished machined condition. All heat treatment shall be performed prior to coating.

When practicable, any acid or alkali cleaning and electroplating shall precede coating. If these processes are to be performed after coating, the coating shall be suitably masked to prevent contact with the solutions involved.

If temperature sensitive materials are to be coated it should be anticipated that surface temperatures up to 350^oF will be produced by the coating process. Where this temperature might present problems, this shall be noted on the drawing.

7. MACHINING PRIOR TO COATING

7.1 ALL PARTS

The final coating and undercoating, when specified, shall only be applied to those areas designated on the drawing. Areas where overspray is permitted should be noted on the drawing. Any such overspray areas shall have the same machining preparations as the required coating areas.

On the areas which are to be coated, the part should be machined undersize on external surfaces, or oversize on internal surfaces, by an amount which will leave a coating thickness of .002/.003 inches (see Para. 7.4) after finish machining. If a metallic undercoat is to be used, then an additional .001-.002 inches shall be allowed for the thickness of this undercoat, unless otherwise specified on the drawing.

Where possible, the coating should be applied in a recess bounded by the base material. This prevents the possibility of chipping the otherwise exposed edges of the coating.

All sharp corners in the areas to be coated shall be broken with a .015/.020 radius unless otherwise specified.

7.2 SHAFTS

The length of the coating, and where specified the length of the undercoating, shall be at least 1/8 inch longer than the bearing so that the coating on the shaft protrudes by 1/16 inches beyond each end of the bearing. This will ensure that the bearing cannot contact any uncoated portion of the shaft.

7.3 BEARINGS

The coating and, where specified, the undercoating will only be applied to the load bearing surface.

It should be noted that the minimum angle which can be used between the nozzle of the equipment and the part to be coated is 45° . Therefore, it is not possible to coat an internal surface in one setup if the length to diameter ratio (L/D) exceeds 1. Turning the part round and applying the coating from the opposite end is necessary for larger L/D ratios. Orifices in internal surfaces which require coating or undercoating shall permit the orifice to taper by 30° inclusive for the thickness of the coating and undercoating, or, alternatively shall permit a radius equal to the thickness of the coating and undercoating.

It is not possible with this technique to produce a groove with a 90° sharp-cornered edge. The groove shall have after-finish machining, a sharp edge with an inclination less than 45° to a plane vertical to the bearing surface, unless otherwise stated.

8. TEMPLATES FOR GROOVED PATTERNS

Templates shall be prepared by photo etching hardened 302 series stainless sheet .010-.020" thick. The photo etching shall be performed from one side of the template only. The etching shall be performed from the side of the template which will be placed against the part during the application of the chrome oxide.

A suitable fixture shall be used to hold the part and the template in the required position, to within the accuracy specified, during the coating process.

The profile of the finished template shall correspond to the bottom of the grooves and have an accuracy in accordance with the tolerances given for the grooves on the finished part. The dimensions of the profile of the grooves in the coating as applied shall be finished dimensions.

9. COATING PROCEDURE

Actual coating of the parts shall be performed as soon as practicable after the surface preparation (Para's. 9.1, 9.2 and 9.3) preferably within two hours.

9.1 All parts shall be thoroughly cleaned free from dust, grit, oil, grease and other foreign materials by vapour degreasing or by washing thoroughly in petroleum solvent and drying.

9.2 All the surfaces to be coated shall be abrasive blasted with No. 16-24 aluminum oxide grit at 80-100 psi to produce a roughened surface which will promote adhesion of the coating. A minimum surface roughness after blasting of 63 microinches, AA, is recommended. In every case, fresh grit shall be used for this abrasive blasting.

When the parts require grooves formed by the ceramic or cermet coating, the abrasive blasting shall be performed before the attachment of the template which is used to form the outline of the required grooved pattern.

Masking shall be used to protect surfaces which are not to be coated. This masking can be done with adhesive-backed tape, shim stock metal shielding or any other appropriate method. Any orifices in the surface shall be plugged with suitable sized wire to prevent grit from penetrating these holes. Larger holes shall be protected with rubber plugs or other suitable material.

9.3 After abrasive blasting, and before coating or under-coating, all temperature sensitive masking materials shall be removed and replaced with metal shim stock or metal shields if these are required to protect finished surfaces. Any holes or orifices will be plugged with graphite or other suitable material to prevent bridging during the coating operation.

9.4 Dry, free-flowing coating and, where specified, undercoating shall be deposited on the designated surfaces in strict accordance with the vendors process operation sheet.

The thickness of the deposited undercoating shall be .001/.002 inches, unless otherwise specified on the drawing. The thickness of the deposited ceramic or cermet coating shall be at least twice as thick as the final thickness of the coating after finish machining. When parts require grooves formed by the coating, the part shall have the undercoating applied before the grooving template is attached. The side of the template from which the pattern was etched shall be placed against the part to be coated.

The temperature of the part being coated shall be maintained so as not to exceed 350°F.

10. FINISH MACHINING OF COATING The bearing surfaces shall be ground and, where necessary, lapped to drawing dimensions and tolerances. The surface finish shall be 8 RMS unless otherwise specified on the drawing. All sharp protruding edges of the coating shall be broken with a .010/015 radius. It is extremely important that proper machining techniques be used to finish the coating. These techniques are described in "Finishing of Flame Plated Parts," copyright 1956 by Union Carbide Corporation and used by Linde Air Products Division.

11. BOND STRENGTH A representative bond strength specimen, machined to the dimension shown in Fig. 2 and prepared and tested in accordance with 11.1, 11.2 and 11.3, shall have a bond strength not less than that specified in Para. 5.

11.1 The portion of the test specimen which is to be coated shall be manufactured from the same material as the part which it represents. The mating part of the specimen may be manufactured from any suitable material. For identification purposes the mating part of the specimen shall be slotted on the 23/32 dia.

11.2 The designated surface of the test specimen shall be prepared in accordance with Paragraphs 9.1 and 9.2, and coated and undercoated when specified, in accordance with Paragraph 9.4. The preparation and coating of the specimen and the parts which it represents shall be performed at the same time and with the same equipment and settings.

11.3 The coating shall be ground until the ceramic or cermet coating is .002/.003" thick. After grinding, the specimen shall be cleaned by vapor degreasing or by rinsing thoroughly in petroleum solvent and drying.

Join and align the test specimen to a clean, dry and grit blasted mating specimen, using Minnesota Mining and Manufacturing Epoxy Cement EC2186.

Care should be taken to avoid the entrapment of air bubbles. Excess adhesive shall be removed from the vicinity of the joint before curing in a circulating air oven for 1 hour at 350°F $\pm$ 20.

The specimens should be pulled on a tensile tester at a rate of .028 inches/minute.

If the bond fails to meet the minimum requirements because fracture occurs at the coating-epoxy interface, the test shall be considered invalid and shall be repeated. When a control sample is tested (i.e. plain, prepared, uncoated specimens joined with epoxy cement), the bond strength shall not be less than 10,000 psi.

12. QUALITY The coating, and when specified the undercoating, shall be adherent to the base material and shall have a uniform surface free from blistering, spalling, chipping, flaking, cracking or other objectionable imperfections.

The coating shall, when finished machined, clean up over the whole of the specified area to be coated when the finished coating thickness is .002/.003 inches. The finished surface of the coating shall be free from metallic or other inclusions foreign to the coating material.

13. CONTROL Control of quality and control of shipments shall be in accordance with the latest issue of MTI Quality Control Manual or as otherwise directed.

14. TOLERANCES The tolerances at the boundaries of the areas designated to be coated shall be defined on the drawing of the part. Tolerances on the thicknesses of the coating shall be as stated in the relevant paragraphs of this specification unless otherwise stated on the drawing of the part.

15. APPROVAL

15.1 Coating shall be performed only by sources approved by MTI Engineering Department.

15.2 Operation sheets covering all details of the coating process for each part shall be submitted by the vendor to MTI Engineering Department for approval. Figure 1 shows a typical operation sheet. Use of format shown in Fig. 1 is not mandatory provided all applicable information shown thereon is reported. Vendor may supplement operation sheets by use of sketches, marked drawings, or notes when necessary.

15.3 To assure adequate performance characteristics, vendor's methods of grinding and/or lapping coating (if grinding and/or lapping is performed) shall be approved by purchaser before parts for production use are supplied, unless such approval be waived.

15.4 Vendor shall use the same coating material, equipment, manufacturing procedures, processes, and methods of inspection for production parts as for approved sample parts. If it is found necessary to make any change which could unfavorably affect any characteristics of the coating, vendor shall submit revised operation sheets to MTI Engineering Department prior to incorporating such change.

16. REJECTIONS Coated parts not conforming to this specification or to authorized modifications will be subject to rejection.