:ORGIA INSTITUTE OF TECHNOLOGY

OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[x] ORIGINAL

[ ] REVISION NO. ____

:oject No. E-25-647

DATE: 9/1/81

:oject Directors: Dr. Ward Winer/Dr. S. Ramalingam

School/~~Lab~~ Mechanical Engineering

ɔonsor: Hughes Aircraft Company, Electro-Optical & Data Systems Group

ɣpe Agreement: Purchase Order No. 04-445624-SL1 (under Gov't Prime #F33615-78-C-5196)

ward Period: From 4/1/81 To ~~10/1/82~~ ~~12/31/83~~ 7/31/83 (Performance) ~~10/1/82~~ 7/31/83 (Reports)

ɔonsor Amount: $156,940

Contracted through: GTRI/~~GIT~~

ost Sharing: N/A

itle: DARPA/AFWAL/HUGHES Solid Lubricated Rolling Element Bearing Program

DMINISTRATIVE DATA

OCA CONTACT Faith G. Costello

) Sponsor Technical Contact: Mr. Michael Gardos, Program Manager, Technology Support Division, Hughes Aircraft Co., Bldg. 6, M/S D-133, Centinela & Teale Streets, Culver City, CA 90230

) Sponsor Admin./Contractual Contact: Roland Neill, Technology Support Division, Hughes Aircraft Co., Centinela & Teale Streets, Culver City, CA 90230, PH (213) 391-0711 ext. 4234

eports: See Deliverable Schedule

Security Classification: See below

efense Priority Rating: DO-A2 under DMS Reg 1

ESTRICTIONS

ee Attached Government Supplemental Information Sheet for Additional Requirements

ravel: Foreign travel must have prior approval - Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

quipment: Title vests with HAC/Government (Reference P.O. Attachment T-1)

OMMENTS: Prior written approval from Hughes is required to release any publicity or any details of this order.

SEP 1981
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GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

## SPONSORED PROJECT TERMINATION SHEET

Date August 9, 1983

5K379

**Project Title:** DARPA/AFWAL/HUGHES Solid Lubricated Rolling Element Bearing Program

**Project No:** E-25-647

**Project Director:** Dr. Ward Winer/Dr. S. Ramalingham

**Sponsor:** Huges Aircraft Company

**Effective Termination Date:** 7/31/83

**Clearance of Accounting Charges:** --

**Grant/Contract Closeout Actions Remaining:**

- [x] Final Invoice ~~and Closing Documents~~
- [ ] Final Fiscal Report
- [ ] Final Report of Inventions
- [ ] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other ____________

**Assigned to:** Mechanical Engineering (School/~~Laboratory~~)

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FORM OCA 10:781

Support Services
E 25-647

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
ECHANICAL ENGINEERING

13 November 1981

Mr. Michael N. Gardos
Program Manager
Technology Support
Hughes Aircraft Company, M.S. D-133
Culver City, California 90230

Subject: Progress Report (30 September 1981 - 31 October 1981)
Purchase Number 04-445624-SL1

Dear Mike:

Attached is the October status report. If you have any questions please call.

Sincerely yours,

Ward O. Winer
Professor and
Principal Investigator

jmv
attachment

cc: W. O. Carlson, Acting Director, Mechanical Engineering
Support Services

PROGRESS REPORT

Reactive Sputtering of TiN and Solid Lubricants
and Shear Strength Testing of Solid Lubricants

PURCHASE ORDER NO: 04-445624-SL1

SUBMITTED TO:

M. N. Gardos
Program Manager
Technology Support
Hughes Aircraft Company, M.S. D-133
Culver City, California 90230

SUBMITTED BY:

S. Ramalingam and W. O. Winer
Principal Investigators
School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

30 September 1981 - 31 October 1981

## I. Coating Trials: Faville-6 Tests

The newly constructed elevated temperature testing rig is of necessity elastically softer than the Faville-6 test simulator that has been used so far. The need to minimize conduction losses to the torque transducer and to prevent overheating of the drive system, tubular drive and torque sensing shafts with thin walls are essential. This renders the test system elastic both in the torsion and in the bending mode. Preliminary testing revealed a chattering problem with the new rig.

Ten sets of Faville-6 sliding test specimens were coated under identical coating conditions (5 test specimen pairs) and evaluated in the original test rig and the elevated temperature test rig (without heating). Tests were carried out at a spindle speed of 630 to 660 rpm with progressively increasing contact load until coating failure occurs. Data from the test runs are as shown below:

| Sample | Original Test Rig | Elevated Temperature Rig |
|---|---|---|
| #4 | Immediate failure at 100 psi | Instantaneous failure at 100 psi on system startup |
| #5 | 100 psi 616 rpm 30 sec<br>200 628 30<br>300 624 30<br>coating failure | coating failure immediately on starting motor |
| #3 | 100 psi<br>failure after 15 sec | 100 psi 660 rpm<br>200 660<br>300 660<br>400 660<br>vibration and failure of 400 psi |

| Sample | Original Test Rig | | | Elevated Temperature Rig | | |
|---|---|---|---|---|---|---|
| #1 | 100 psi | 635 rpm | 30 sec | 100 psi | 660 psi | 30 sec |
| | 200 | 635 | 30 | 200 | 660 | 30 |
| | 300 | 634 | 30 | 300 | 660 | 30 |
| | 400 | 633 | 30 | 400 | 658 | 30 |
| | 500 | 631 | 30 | 500 | 658(?) | 30 |
| | 600 | 627 | 30 | 600 | 655 | 30 |
| coating survived 600 psi | | | | at 800 psi, hexadecane started to smoke. at 1000 psi vibration started. Test was stopped. Coating survived 1000 psi. | | |
| #2 | 100 psi | 639 rpm | 30 sec | 100 psi | 680 rpm | |
| | 200 | 636 | 30 | 200 | 680 | |
| | 300 | 636 | 30 | 300 | 680 | |
| | 400 | 634 | 30 | 400 | 680 | |
| | | | | 500 | 680 | |
| coating failed at 400 psi | | | | coating failed at 500 psi without initial vibration. | | |

This test program indicates that the test rigs are, by and large, similar. Elevated temperature rig is prone to severe vibration during testing, especially in the initial stages. It often tends to accelerate failure. The scatter in failure load will now have to be reduced in order to assure coating reliability.

Note: Well-bonded, reproducible coatings are produced when W. T. Bean's metal conditioner is used to prepare test samples for coating. Metal conditioner produces pitting artifacts in test samples. A major goal of the present program is to produce well-bonded coatings without pitting artifacts. A cleaning procedure identical with that used by Hughes Aircraft for $MoS_2$ coating is presently being used, i.e., vapor degrease, oakite clean, alcohol and water rinse.

## 2. Parametric Coating Studies

In order to lower the scatter in failure loads with Oakite HD 124 cleaning, a parametric test program has been undertaken.

The M-50 and T-15 test materials allow sample heating to 1000°F without adverse metallurgical consequences. Hence sample pre-heat temperature (prior to coating) is being used as a test variable (400°F; 600°F; 800°F). Heating time is a second variable (30 minutes; 45 minutes). Specimen location in the coating chamber is the third variable.

The test results obtained, with the old test rig, will be reported in the next program period.

## 3. Proof Test Conditions

Measured torques in Faville-6 tests, in the first phase concluded last year and in the present series of tests, yield sliding friction coefficient of 0.12 to 0.15.

Note: There is an apparent test rig effect. The two test rigs do not yield identical $\mu$ values under identical test conditions.

Power dissipation at a contact load of 1000 psi at 660 rpm yield values of 0.25 hp. Since test specimens only possess a contact surface of 0.2 $in^2$, the dissipation density ($watts/cm^2$) is large, even under the test conditions used.

Contact stresses to 2500 psi and test speeds to 4000 rpm are estimated to yield a power dissipation density of $1.56 \times 10^3$ watts/cm$^2$, which is unrealistically large.

The tests, under these conditions will cause thermally induced film failure. It is unlikely to be a satisfactory indicator of coating-to-substrate adhesion. As agreed in the telephone conversation of October 27, our proof tests will be based on 500 psi sliding contact tests at up to 2000 rpm.

Note: Severe "burning" of n-hexadecane was noted in the 1000 psi; 660 rpm tests. Duplex coated samples (Westinghouse compact on TiN) will undergo solid to liquid transition under the condition due to the melting of the In/Ga eutectic. Duplex coated test samples may only permit contact stresses less than 500 psi at the highest test rpm.

4. Bale Coating

Bale coating with a fixture essentially similar to that used by Hughes (Ron Christy) has been evaluated. It differs from Christy's in that the rotation axis is not co-axial with the sputtering target.

A modified four-bar linkage system has been assembled and is presently being tested. Test results will be reported in the next progress report.

Work is also being done to modify the ball coating fixture in order to permit fixture rotation co-axial with the target.

5. Elevated Temperature Traction Test Rig

Progress was made toward the completion of the high temperature traction instrument. The roller arbor drive mechanism was designed and fabricated this month. The traction force transducer and disc spindle fixture are being designed. This fixture will allow variation of side-slip during high-temperature traction measurements. Remaining to be completed are the disc spindle drive system, drive motor power transmission and peripheral instrumentation (thermocouple, tach, etc.). The entire instrument should be ready by the first of the year.

6. Modified High Load Friction and Life Tester

Experience has been gained in the testing of TiN coated sliding Falex 6 specimens at room temperature with the high temperature friction and life tester mentioned in last month's progress report (Figures 5,6, and 7). Nominal contact stresses of 1000 psi have been successfully run but spindle speed was motor torque limited to about 700 rpm. A more rigid test fixture is being designed in hope of improving test repeatability and a new motor variable speed drive has been obtained. The new motor/drive unit may enable higher test speeds.

E-25-647

GEORGIA INSTITUTE OF TECHNOLOGY

ATLANTA, GEORGIA 30332

SCHOOL OF
HANICAL ENGINEERING

20 January 1982

Mr. Michael N. Gardos
Program Manager
Technology Support
Hughes Aircraft Company, M.S. D-133
Culver City, California 90230

Progress Report: 15 Nov 1981 to 15 Jan 1982
Hughes P.O. Number 044445624-SL1

Dear Mike:

Attached is the subject report which Ram and I discussed with you on the telephone yesterday. If you have any questions, please call.

Sincerely yours,

Ward O. Winer
Professor and
Co-Principal Investigator

jmv

xc: S. Ramalingam
W. O. Carlson
OCA ✓

attachment

PROGRESS REPORT

# Reactive Sputtering of TiN and Solid Lubricants and Shear Strength Testing of Solid Lubricants

PURCHASE ORDER NO: 04-445624-SL1

SUBMITTED TO:

M. N. Gardos
Program Manager
Technology Support
Hughes Aircraft Company, M.S. D-133
Culver City, California 90230

SUBMITTED BY:

S. Ramalingam and W. O. Winer
Principal Investigators
School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

15 November 1981 to 15 January 1982

# PROGRESS REPORT

Progress in the development and characterization of hard and soft coatings for rolling contact bearings are outlined in the following sections. Parametric studies of coating of Faville-6 test samples, evaluation of their tribological characteristics, ball coating and the construction of an elevated temperature traction test rig were the principal activities in this time period.

## A. Parametric, hard coating studies

The continued parametric study involved the assessment of the effect of surface preparation and coating practice on the coating-to-substrate bond strength. Based on the study, the following practice has been evolved.

(a) Use of "metal conditioner" made by W. T. Bean Co., Detroit, Michigan, for surface conditioning degreased test samples;

(b) ethanol rinse;

(c) dry, load in vacuum system and pump down to a pressure less than $1 \times 10^{-5}$ Torr;

(d) preheat for 30 minutes at $600^{\circ}$F;

(e) reactive sputter coat.

This practice enables survival of the hard coats at Faville-6 contact pressures of 500 - 1000 psi for several minutes at up to 500 rpm.

Auger spectroscopy of coated samples reveals an abrupt steel-TiN interface. The hard coat itself contains oxygen. Modification of coating practice is essential to rectify this film-substrate interface and film structure. An oxygen feed line has been installed to bleed small quantities of oxygen prior to step (e) to produce a semi-graded (metal-oxide-hard coat interface). An oxygen trap has been installed in the $Ar/N_2$ bleed line to purify process gases. The latter is meant to lower, if not eliminate, oxygen in the hard coat.

Satisfactory coatings are now being produced which await tribological and durability evaluation in the Faville-6 simulator.

B. Modification of Faville-6 Simulator

To improve the ease and accuracy of test sample positioning and to minimize the vibration due to the belt drive, the test rig has been modified. The reconfigured system enables test speeds to 2000 rpm at variable contact pressure.

The test system is now a direct drive system. Two micrometers are used to center the test samples carried by the load cell. This is essential for testing coated thrust bearings where alignment of the races is essential. The modification also enables interpositioning of a heated chamber to carry out Faville-6 tests at up to 600°F.

Mechanical modifications are complete. Some electronic maintenance work in the SCR power supply is now in progress.

Faville-6 tests will be initiated with minimal delay in order to obtain data for the semi-annual report due by 15 Feburary 1982.

C. Ball Coating

The rotary fixture initially designed for ball coating had a fixture rotation axis offset with respect to the sputtering head. Coatings produced were prone to shadow effects. Mixed coats of Ti and TiN were obtained. The coating system has been modified to remove this deficiency.

A set of balls (full complement for the thrust bearing) have been coated and tested successfully at room temperature and a bearing load of 200 lbs at 500 rpm. The test load corresponds to a hertz pressure of 140,000 psi. Subsequent tests did exhibit variability in film-to-substrate adhesion resulting in failure.

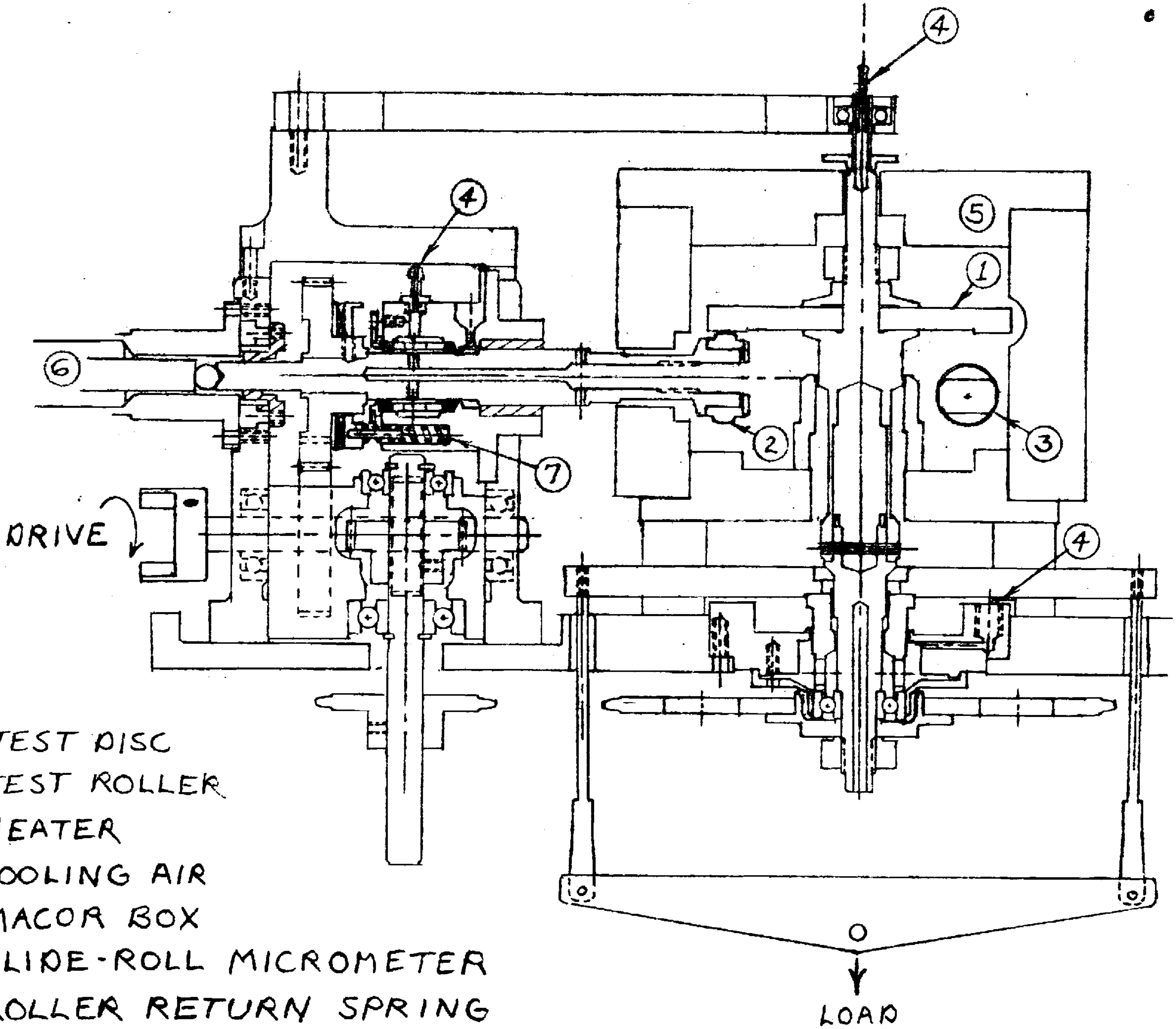
The problem has been traced to back streaming contamination from the diffusion pump. A CT 100 liquid nitrogen baffle has been purchased to eliminate this problem. Additional coating and bearing tests will follow, the incorporation of the $LN_2$ baffle in the coating system.

D. Elevated Temperature Traction Test Rig

A test rig suitable for traction measurement at elevated temperatures has been built and tested. It possesses a heating assembly enclosed by a Marcor chamber, a sapphire window for I.R. temperature measurement and a precision load cell. A traction curve obtained with the rig at room temperature is appended as Figure (1 m/s; 1.5 GPa; 20$^{o}$C).

Preliminary tests have been conducted at temperatures to 315$^{o}$C in which a complete traction curve has been obtained. Traction discs and rollers (T-15 and M-50) are currently being fabricated. It is expected that some elevated temperature traction tests can be carried out by February 15, in time for the semi-annual report. Tests on TiN and Westinghouse compact coated discs are projected.

# HIGH TEMP. TRACTION INSTRUMENT




(1) TEST DISC
(2) TEST ROLLER
(3) HEATER
(4) COOLING AIR
(5) MACOR BOX
(6) SLIDE-ROLL MICROMETER
(7) ROLLER RETURN SPRING

S. BAIR
12/11/81

# Georgia Institute of Technology

A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF MECHANICAL ENGINEERING
ATLANTA, GEORGIA 30332


14 April 1982

Mr. Michael N. Gardos
Program Manager
Technology Support
Hughes Aircraft Company, M.S. D-133
Culver City, California 90230

Subject: Progress Report P.O. #04-445624-SL1
7 February 1982 to 9 April 1982

Dear Mike:

Enclosed are copies of our progress report to meet the requirements of our contract. Please let us know if it meets with your approval.

Very truly yours,

Ward O. Winer
Professor and
co-Principal Investigator

jmv
enclosure

xc: Dr. Walter O. Carlson, Acting Director
School of Mechanical Engineering
S. Ramalingam, co-Principal Investigator
Reports Coordinator (OCA)

PROGRESS REPORT

Reactive Sputtering of TiN and Solid Lubricants
and Shear Strength Testing of Solid Lubricants

PURCHASE ORDER NO: 04-445624-SL1

SUBMITTED TO:

M. N. Gardos
Program Manager
Technology Support
Hughes Aircraft Company, M.S. D-133
Culver City, California 90230

SUBMITTED BY:

S. Ramalingam and W. O. Winer
Principal Investigators
School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

7 February 1982 to 9 April 1982

1. Faville-6 Tests

Ten sets each of T-15 and M-50 Faville-6 flat test samples suitable for sliding contact tests have been coated. They are ready to be shipped to M. Gardos for Tribo-tube overlay coating in Switzerland.

Coating procedure used, non-distortive sputter coating, has been tested in our Faville-6 simulator at room temperature (500 psi, 1000 rpm runs) for up to 12 minutes without failure. Test samples have been observed to fail by a ridge formation within the sliding contact region and subsequent film failure at groove edge. SEM examination reveals raised lips on either side of the groove. Non-dispersive x-ray analysis indicates that the material of the groove and of the raised lip are identical in composition. Systematic analysis of failure is in progress.

Carbon blocks furnished by Hughes are now being coated for Auger analysis at N.R.L. A pair of T-15 and M-50 samples are also being overlayed with TiN for Auger work at Georgia Tech to track film failure mechanism.

Additional coating and evaluation work are in progress.

2. Ball Coating

The re-configured ball coating system is now functional. Four batches of 1/4 in. balls (52100) have been coated and tested with bare races. Test results are as follows:

THRUST BEARING TESTS

Bare Races; TEFLON Cage; 12 Balls,
n-Hexadecane 'Lubricant'

| Coating Thickness | Air Pressure/Load | Hertz Pressure | rpm | Time | Result |
|---|---|---|---|---|---|
| 0.41µm | 50 psi/200 lb | 110 kpsi | 500 | 15 | 2 Balls Failed |
| 0.21µm | 50 psi/200 lb | 110 kpsi | 506 | 15 | No Failure |
| 0.41µm | 50 psi/200 lbs | 110 kpsi | 502 | 30 | No Failure |
| 0.21µm | 80 psi/320 lbs | 130 kpsi | 522 | 30 | No Failure |

Four sets of bearing races are currently being coated with TiN for tests with TiN coated balls. The results will be reported in the next progress report. Additional tests at higher Hertz forces are also scheduled with bare races.

3. Traction Tests

Further tests at elevated temperatures await arrival of material for roller fabrication (from Hughes). The elevated temperature traction test rig is functional. Data have been furnished in the previous report with 52100 rollers riding on M-50 discs overlay coated with TiN.

4. Elevated Temperature Faville-6 Tests

A rig for elevated temperature durability tests is in design and will be constructed shortly. Redesign and construction is made necessary by the lack of stiffness in the first system assembled.