III. TEST RESULTS

*There is no doubt The **TIODIZE PROCESS** is an unprecedented quality treatment for titanium. It's a must.*

III. TEST RESULTS

USAGE FOR THERMAL CONTROL: INSAT-I DOMESTIC SATELLITE SYSTEM FOR INDIA

The Western Development Laboratories Division (WDL) of Ford Aerospace Communications Corporation (FACC) was chosen by the Government of India to design and build the first generation spacecraft for the Indian National Satellite System … INSAT-1. This spacecraft (shown in Figure 3-1) will introduce sociological and economical advantages of modern communications to India's population which exceeds 613,000,000 and covers a land area measuring 3,280,483 square kilometers. INSAT-1 will provide reliable communication capability to India's rugged terrain and inaccessible regions far more economically than any alternative high quality terrestrial system.

To accomplish the satellite's major communications, direct broadcast satellite service, meteorology and data collection missions, it will be placed in geostationary orbit 35,784 Km above India and will employ a single 445-newton (100 pound) thruster for apogee boost. During design and development of the thruster at WDL, protection of adjacent structure against the plume was considered necessary. Titanium was the best lightweight choice for a shield, provided the thermal absorptivity/emissivity of less than 1.0 could be achieved. The TIODIZE Type I Process has these characteristics, and samples of 6Al-4V titanium were coated by TIODIZE Co., Inc. and evaluated by WDL utilizing the Gier Dunkle Source Transfer Optical System. Subsequently, preformed parts of the flight hardware were coated, and test samples were processed with the parts to verify thermal characteristics. Results of WDL tests on these test samples are presented below:

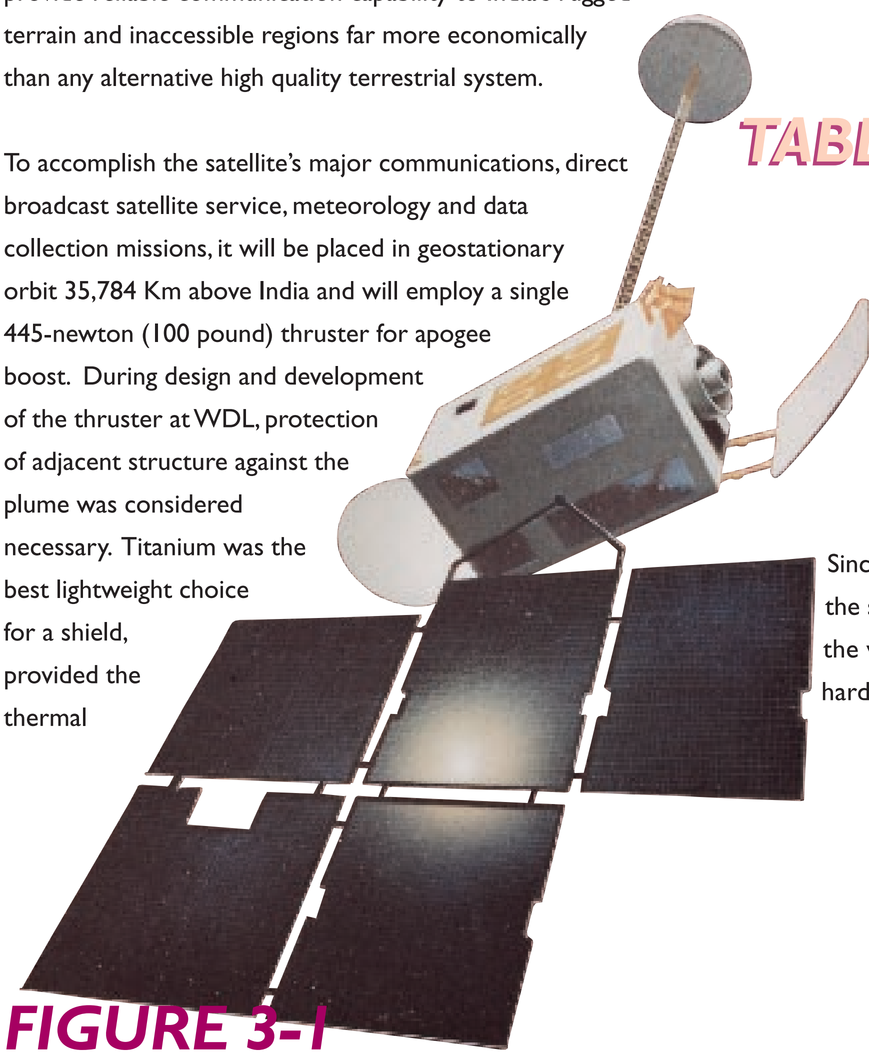


FIGURE 3-1

This spacecraft will introduce sociological and economical advantages of modern communications to India's population. Titanium was the choice for a shield coated with TIODIZE Type I process.

TABLE III-1

I. Single Coating (samples run with production parts)

Sample	#1	#2	#3	#4	#5
Absorptivity (αs)	.71	.70	.67	.63	.69
Emissivity (n)	.80	.81	.83	.85	.82
$\frac{\alpha s}{n}$	.89	.86	.81	.74	.84

TABLE III-2

II. Double Coating (pretest sample only-not used in production)

Absorptivity (αs)	.58
Emissivity (n)	.89
$\frac{\alpha s}{n}$	.65

Since the desired αs/ n of less than 1.0 was achieved by the single coating, the heavier coating used to achieve the very low ratio was not used for production hardware. For additional testing, see page 12.

TIODIZE PROCESS

III. Test Results

ABSORPTANCE AND EMITTANCE TESTS

Another significant use for the TIODIZE PROCESS is the control of thermal radiation. The solar absorptance (αs) and normal emittance (n) for ULTRA V-E17 and bare Type I and II TIODIZE PROCESS coatings were found to be as shown below:

TABLE III-3

	TYPE I		TYPE II BARE
	Bare	*Ultra V-E17*	
(αs)	0.62	0.89	0.82
(n)	0.89	0.91	0.51

The specimens were made of Titanium 6Al-4V foil, .005 inches in thickness, and TIODIZED as shown. The ULTRA V-E17, when used, was TIODIZE® black organic coating.

The absorptance was determined by the 19 point integration between 0.32 and 2.1 microns wavelength. The emittance was arrived at by a 25 point integration between 4.8 and 26.2 microns. Spectral measurements were made in either a heated Hohlraum chamber or a Gierdunkle integrating sphere with an incident angle of 20 degrees on specimens water cooled to approximately room temperature.

TABLE III-4

GENERAL ELECTRIC SPACECRAFT MATERIALS RESEARCH AND DEVELOPMENT LABORATORIES EMITTANCE TEST RESULTS

Test Service Report
Test Service Number 6290

29 September 1987

S.O. NO.	*1 D20-FE-5620-00*
MATERIAL	*5 sets of samples from Tiodize Co., Inc.*
DESCRIPTION	*2 discs and 2 panels per set*
TEST	*Emittance, Normal (100°F) Gier Dunkel*
PROCEDURE	*Adhesive per F.T.S. No. 141, Method 6301*

TEST RESULTS:

Sample	*Description*	*Color*	*Emittance*	*Adhesion*
A	*TIODIZE Type II all over Ultra VE-17 one side No Top Coat*	*Black*	*.928 .923*	*No Loss*
B	*Same as A, except with Top Coat*	*Black*	*.936 .934*	*No Loss*
C	*TIODIZE Type I all over Ultra VE-17 one side No Top Coat*	*Black*	*.946 .947*	*No Loss*
D	*Same as C, except with Top Coat*	*Black*	*.950 .951*	*No Loss*
E	*TIODIZE Type I all over +K-seal*	*Tan*	*.932 .946*	*Some loss on side 1 of each panel; No loss on reverse side of each panel.*

VACUUM OUTGASSING TEST

TABLE III-5

5 Ford Aerospace & Communications Corporation
TEST REQUEST #87-2050

ITEM OR PART NO.
Ultra VE 17

MANUFACTURER TIODIZE CO., INC.
Tiodize Co., Inc.

Required Tests	*Test Method Used*	*Test Results*	*Requirements*	*Pass/Fail*
Outgassing	ASTM E595	TML = 0.9100% VCM = 0.0000%	TML 1.0% VCM 0.1%	PASS

Comments:
TML, VCM-Material meets outgassing requirements.

TIODIZE PROCESS

III. FATIGUE TEST RESULTS
BELL HELICOPTER COMPARATIVE FATIGUE TEST RESULTS

Mr. Thomas R. Adams
TIODIZE CO., INC.
5858 Engineer Drive
Huntington Beach, CA 92649
(714) 898-4377

Dear Tom:

In referenced letter we requested that you coat our prepared samples of 6al, 4V titanium alloy by your Tiodize Method. We stated that we intend to compare the fatigue strength of these samples with similar samples treated by the phosphate-fluoride process and other samples without any surface treatments. The results of the fatigue test of surface treated and untreated titanium sheet stock were as follows:

Fatigue strength plain titanium = 74,910 psi;

Fatigue strength phosphate-fluoride titanium - 86,770 psi;

Fatigue strength Tiodize titanium = 99,580 psi.

Since these specimens indicated improved fatigue strength, we would like, in the near future, to evaluate treated samples of Heywood lug specimens. We will have these specimens prepared in our Machine Shop and then send them to you for the Tiodize treatment.

Yours very truly,
BELL HELICOPTER COMPANY
Chemical & Process Lab

III. Test Results

FATIGUE TESTS INTRODUCTION

Titanium alloys will comprise a significant portion of the primary structure of the next generation aircraft. Their increased use is based on high performance resistance, high strength to weight ratio, good fatigue properties and excellent corrosion resistance. Like other high strength alloys used in airframe construction, titanium is susceptible to fretting damage. Such damage may weaken a structure and possibly cause premature fatigue failure. Because of its known tendencies to seize and gall, titanium could possibly be critical in this regard.

FATIGUE FAILURE DUE TO FRETTING DAMAGE

Historically, the fretting fatigue of high strength alloys has been alleviated by preventing contact between surfaces. This approach includes insertion of bushings, and application of coatings and surface treatments. Because minimal work had been performed on titanium in airframe structures, a program (F33615-70-C-1538) was set up in 1970 to investigate surface treatments and coatings to alleviate fatigue in titanium alloys. That contract study included the definition of fretting conditions in a titanium structural joint, selection of candidate coatings to prevent fretting damage, and coating evaluation in a fretting-fatigue critical situation. The program was conducted by MCAIR during the period 18 May 1970 and 18 June 1971.

THE EFFECT OF COATINGS ON FATIGUE RESISTANCE

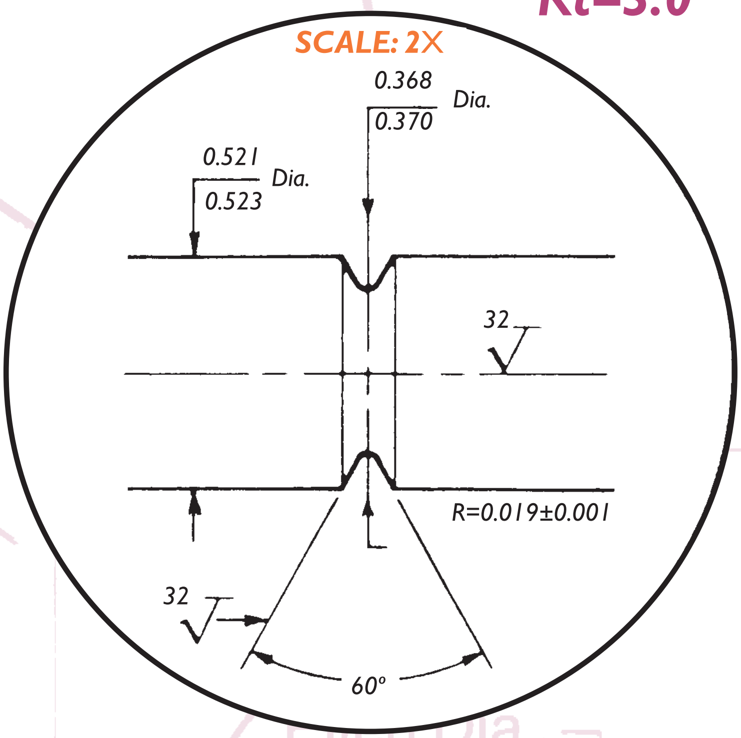
Many of the coatings available to reduce wear and fretting damage can also reduce the fatigue resistance of the alloy to which they are applied. To characterize their fatigue effect, coatings were tested on smooth unnotched Ti-6Al-6V-2Sn specimens in a previous study. Similar coatings on a notched specimen were tested at lower stress, to better approximate conditions of actual airframe structures.

MATERIAL CERTIFICATION

The specimens were all machined from 1 in. diameter Ti-6Al-6V-2Sn bar, annealed, RMI Company Heat No. 704570. This material was purchased to MIL-T-9047, Type 3, Composition C. Certification test results follow.

HYDROGEN CONTENT:	36 PPM
ACTUAL DIAMETER:	1.010 IN.
FTY:	150,000 PSI
FBU:	160,000 PSI
ELONGATION:	19%

FIGURE 3-2 NOTCHED FATIGUE SPECIMEN Kt=3.0



VIEW A.A. (Enlarged)

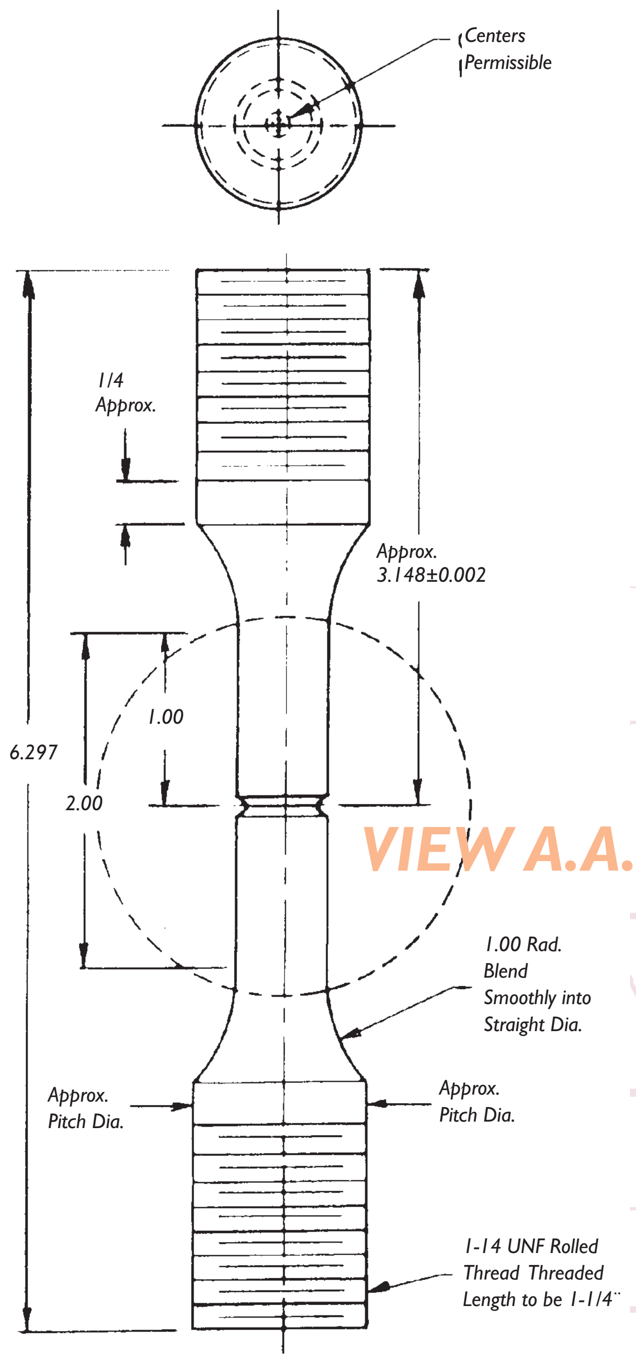
All Dimensions in Inches.

Notes: 1. Concentricity of notch and threads. 0.001 FIR.
2. Concentricity of notch and reduced dia. section, 0.002 FIR.

III. Test Results

SPECIMEN FABRICATION

Fifty-four specimens were machined on a lathe to the design of Figure 3-2. The notches were machined into the finished specimens with a single point tool ground to the required geometry. During the initial testing of control specimens, there was some microscopic roughness observed in the notches. All subsequent test specimens were lightly polished on the notch using 400 grit paper while turning in the lathe.



TESTING

Specimens were tested at constant amplitude on a Sonntag SF-10-U fatigue machine. The specimens initially fatigue tested to develop an S-N curve, yielded wide spread in data. Sanding the notches of the remaining specimens greatly lessened the data scatter. Twenty-four uncoated control specimens were tested to develop the curve. From this data, sixty ksi net stress was chosen for fatigue tests of the coated specimens.

RESULTS

The individual test results for all the specimens are listed in Table III-6 (on page 16). Of the coatings and surface treatments tested in the last half of the task, only TIODIZE® and a shot-peening compare favorably to the control specimens at 60 ksi. All of the specimens except for those shot-peened and TIODIZED had multiple fracture origins on the surface. These latter two treatments produced single point fracture origins.

Shot-peening is well documented for its effect in improving fatigue resistance through the compressive stresses induced in the surface. TIODIZE PROCESS anodic coating improves fatigue strength through the complex surface treatment by which it becomes an interstitial part of the basic metal. The coating was continuous and did not flake off at the fracture area.

Shot-peening and TIODIZE® are processes easily applied to structural parts, and relatively low in cost. For these reasons, and their enhancement of fatigue resistance in tests, both processes were selected for additional fretting fatigue tests.

A comparison of the most promising surface treatments was conducted. These included shotpeening and TIODIZE® for its fatigue resistance in the 1971 study. It was already concluded that salt exposure was an important parameter in fretting-fatigue, therefore, a qualitative comparison was made in salt spray. The 2 x 2 inch coupons used in the test were coated, exposed to salt spray, dried and compared. There was no apparent absorption of salt solution by any of the coatings. Water rinsing easily removed the dried deposits. There was no special affinity for salt to deposit on any of the coatings.

TABLE III – 6: TEST DATA FOR TASK 4 SPECIMENS

SPECIMEN NO	NET STRESS (ksi)	CYCLES TO FAILURE	CONDITION WHEN TESTED
Uncoated, Control			
1	*80*	*2,000*	*As Machined**
2	*50*	*67,000*	*As Machined**
3	*35*	No Break	*As Machined**
8	*35*	No Break	*As Machined**
2-2	*80*	*1,000*	*As Machined**
3-3	*50*	*368,000*	*As Machined**
5	*50*	*34,000*	*As Machined**
6	*45*	*70,000*	*As Machined**
9	*45*	*61,000*	*As Machined**
10	*45*	*1,406,000*	*Machined, Shot Peened 0.0101A**
50	*45*	*345,000*	*As Machined**
51	*50*	*18,000*	*As Machined**
11	*50*	*108,000*	*Machined, Shot Peened 0.010A**
12	*50*	*329,000*	*Machined, Shot Peened 0.010A**
52	*50*	*237,000*	*As Machined*
53	*50*	*2,106,000*	*As Machined*
54	*50*	*69,000*	*As Machined*
55	*50*	*50,000*	*Machined, Chem Milled 0.020 in. on Dia*
56	*60*	*34,000*	*As Machined*
57	*60*	*857,000*	*As Machined*
58	*60*	*27,000*	*As Machined*
46	*60*	*28,000*	*As Machined*
47	*60*	*40,000*	*As Machined*
48	*60*	*49,000*	*As Machined*
Coated			
16	*60*	*1,013,000*	*"TIODIZE" ANODIZED*
17	*60*	*1,172,000*	*"TIODIZE" ANODIZED*
18	*60*	*1,250,000*	*"TIODIZE" ANODIZED*
19	*60*	*18,000*	*MCAIR Anodized*
20	*60*	*16,000*	*MCAIR Anodized*
21	*60*	*15,000*	*MCAIR Anodized*
13	*60*	*23,000*	*Fluoride-Phosphate Coated*
14	*60*	*19,000*	*Fluoride-Phosphate Coated*
15	*60*	*22,000*	*Fluoride-Phosphate Coated*
22	*60*	*9,000*	*"Kanigen" Electroless Ni, 0.0005 in., 550ÞF - 4 hr.*
23	*60*	*8,000*	*"Kanigen" Electroless Ni, 0.0005 in., 550ÞF - 4 hr.*
24	*60*	*9,000*	*"Kanigen" Electroless Ni, 0.0005 in., 550ÞF - 4 hr.*
28	*60*	*20,000*	*Tungsten Carbide, Plasma Sprayed 0.003-0.005 in.*
29	*60*	*25,000*	*Tungsten Carbide, Plasma Sprayed 0.003-0.005 in.*
30	*60*	*24,000*	*Tungsten Carbide, Plasma Sprayed 0.003-0.005 in.*
25	*60*	*26,000*	*Al-Bronze, Plasma Sprayed 0.003-0.005 in.*
26	*60*	*26,000*	*Al-Bronze, Plasma Sprayed 0.003-0.005 in.*
27	*60*	*26,000*	*Al-Bronze, Plasma Sprayed 0.003-0.005 in.*
34	*60*	*81,000*	*"Tibon" Chromium Plate, 0.0005 in.*
35	*60*	*85,000*	*"Tibon" Chromium Plate, 0.0005 in.*
36	*60*	*57,000*	*"Tibon" Chromium Plate, 0.0005 in.*
37	*60*	No Break	*Shot Peened, 0.006-0.008A***
38	*60*	*252,000*	*Shot Peened, 0.006-0.008A*
39	*60*	No Break	*Shot Peened, 0.006-0.008A***
40	*60*	*11,000*	*Nickel-Diamond Plate, 0.0005 in.*
41	*60*	*12,000*	*Nickel-Diamond Plate, 0.0005 in.*
42	*60*	*11,000*	*Nickel-Diamond Plate, 0.0005 in.*
43	*60*	*10,000*	*IVD Copper Plate, 0.0005 in.*
44	*60*	*10,000*	*IVD Copper Plate, 0.0005 in.*
45	*60*	*12,000*	*IVD Copper Plate, 0.0005 in.*

* *These specimens were taken from the lathe as-machined. All other specimens were polished in the lathe with 400 grit Al_2O_3 paper after machining of the notch.*

** *Fatigue test was stopped at 2,500,000 cycles.*
Frequency = 30 cps.

Stress Ratio $= \frac{\text{Minimum}}{\text{Maximum}} = +0.1 \quad K_t = 3$

III. Test Results

LFW-1 FRETTING WEAR TEST

Scope

Stainless steels and most titanium alloys are notorious for their fretting wear tendencies. Fretting wear will occur when contacting surfaces are undergoing small, oscillatory, tangential displacements. Fretting wear or "Fretting corrosion" is actually a combination of adhesive (transfer of wear particle), corrosive (where the particle oxidizes and becomes usually much harder), and abrasive wear (particle removes material from opposing surface).

The best way to reduce fretting wear is to minimize interfacial slip between the contacting surfaces with solid film lubricants or soft metallic coatings such as cadmium, silver, tin, lead or indium. The problem with these metallic soft coatings is that they create the undesirable side effects of diffusion and intergranular corrosion. This is particularly true with titanium-hydrogen embrittlement.

This section will show how specially formulated solid film lubricants applied over the TIODIZE PROCESS can effectively reduce fretting wear on titanium alloys.

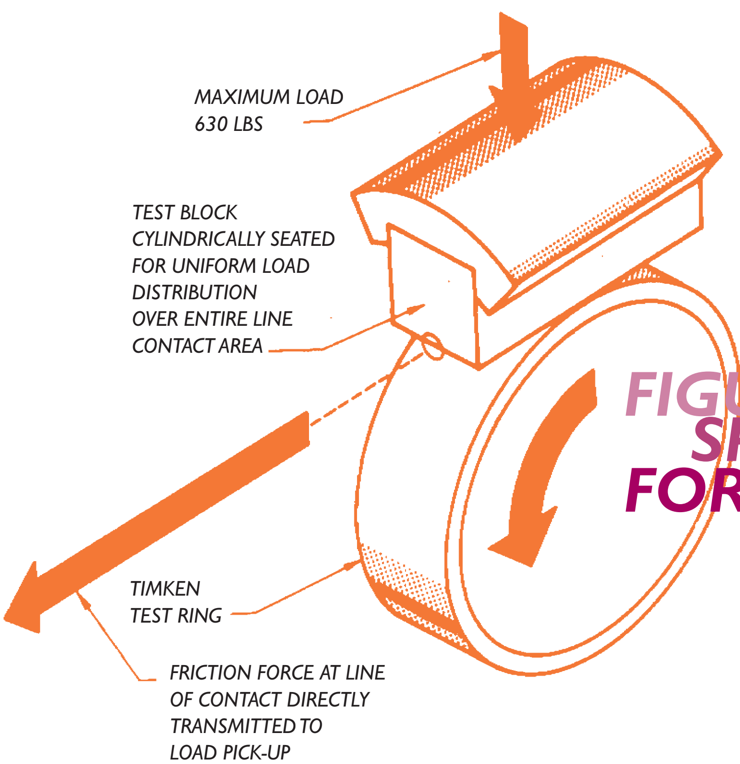


FIGURE 3-3 LFW-1 TEST SPECIMENS AND FORCE DIAGRAM.

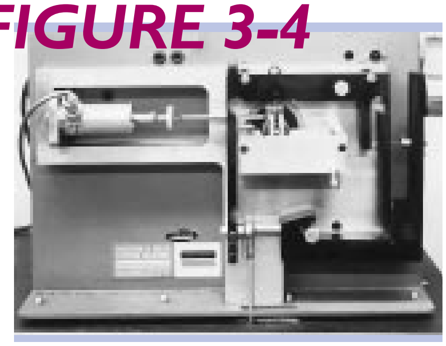
CANDIDATE MATERIALS

Aside from the MIL-L-8937, MIL-L-46010 and MIL-L-81329, solid film lubricants, the specially formulated TIOLUBE 460 and 1175, the result of extensive research programs, were also included. Tests were performed on bare SAE 4620 (Rc 58-62) steel oscillating against E 9310 and hardened (Rc 50-55) alloy steel, and Ti-6Al-4V against Ti-6Al-4V treated with the TIODIZE PROCESS. The bare steel sliding against bare steel, as well as the bare titanium against bare titanium, are given here strictly for reference purposes.

TEST CONDITIONS

The LFW-1, illustrated in Figures 3-3 and 3-4 was utilized, with an oscillatory mode of an 8Þ arc only, equaling a 0.1ý displacement at a speed of 102 cpm. Failure criterion was a preselected maximum kinetic friction coefficient of .50 with the bare steel and titanium, and .35 with the others. Two bearing pressures were chosen: 50,000 and 100,000 psi, designated as low and high respectively. After initial trial test runs, the high bearing pressure for the bare steel-titanium combination was lowered to 70,000 psi due to excessively high friction coefficients.

FIGURE 3-4



LFW-1 LUBRICANT TEST MACHINE

III. Test Results

TEST RESULTS

The results in Table III-7 clearly indicate that the kinetic friction coefficient is substantially reduced by treating the titanium, as compared to the bare steel combination. The longest wear life was obtained with the 1175 solid film lubricant over TIODIZE Type II treated Ti-6Al-4V. The 1175 appears to be superior to the other solid film lubricants tested. This is shown in the last test (see Table III-7) where it exhibited a consistently long wear life in excess of 200,000 oscillations at both bearing pressures.

TABLE III-7: LFW-1 OSCILLATORY FRETTING WEAR TEST RESULTS

LFW-1 RING VERSUS BLOCK	PRETREATMENT RING	PRETREATMENT BLOCK	SOLID FILM LUBRICANT	Mμ RANGE [1]	ARCS [5]	OSCILLATIONS TO FAILURE
SAE 4620 E9310	Bare	Bare	None	.40-.43 .42-.45	8þ	6,953 2,497
Ti-6Al-4V Ti-6Al-4V	Bare	Bare	None	.48-.52 .50-.57	8þ	1,056 793
Ti-6Al-4V E9310	TIODIZE Type I	Bare	MIL-L-8937	.13-.27 .08-.17	8þ	9,573 13,247
Ti-6Al-4V Ti-6Al-4V	TIODIZE Type I	TIODIZE Type I	MIL-L-8937 [2]	.10-.17 .07-.12	8þ	22,370 17,952
Ti-6Al-4V Ti-6Al-4V	TIODIZE Type I	TIODIZE Type I	MIL-L-46010 [2]	09-.19 .07-.15	8þ	19,230 10,950
Ti-6Al-4V Ti-6Al-4V	TIODIZE Type I	TIODIZE Type I	MIL-L-81329 [2]	.12-.20 .10-.18	8þ	11,037 32,832
Ti-6Al-4V Ti-6Al-4V	TIODIZE Type I	TIODIZE Type I	TIOLUBE 460 [2]	.07-.18 .06-.13	8þ	70,133 20,891
Ti-6Al-4V Ti-6Al-4V	TIODIZE Type II	TIODIZE Type II	MIL-L-81329 [2]	.14-.22 .12-.18	8þ	7,985 11,392
Ti-6Al-4V Ti-6Al-4V	TIODIZE Type II	TIODIZE Type II	TIOLUBE 460 [2]	.07-.17 .07-.11	8þ	90,855 79,012
Ti-6Al-4V Ti-6Al-4V	TIODIZE Type II	TIODIZE Type II	TIOLUBE 1175 [2]	.03-.09 .03-.05	8þ	289,150 252,680
Ti-6Al-4V AERMET 100	TIODIZE Type IV	GRIT BLAST	TIOLUBE 460 [3] ON ALUMAZITE Z	.03-.07 [4]	3þ	28,251
Ti-6Al-4V AERMET 100	TIODIZE Type IV	GRIT BLAST	ALUMAZITE [3] ZY-138	.01-.03 [4]	3þ	288,145
Ti-6Al-4V AERMET 100	TIODIZE Type IV	GRIT BLAST	TIOLUBE 460 [3]	.04-.10 [4]	3þ	109,596

NOTES: Unless otherwise specified

[1] The first value is the low bearing pressure - 50,000 psi.
The second value is the high bearing pressure - 100,000 psi.
[2] In all titanium versus titanium tests, both surfaces were lubricated.
[3] Block only coated
[4] Coefficient of friction range at 30,000 psi bearing pressure.
[5] 3þ = 0.036 inches 8þ = 0.1 inches.

III. Test Results

LFW-1 UNIDIRECTIONAL WEAR TEST RESULTS

Titanium VS 4130 Steel

LFW is a block on rotating ring testing machine used to determine wear life and coefficient of friction. Ring rotational speed used in this test was 110 rpm which equates to approximately 475 in/min linear sliding velocity.

The rings used in this test were titanium 6Al-4v alloy. The blocks were 4130 heat treated to Rc 26-28.

The actual p.s.i. load on the block was difficult to estimate during the test because the wear scar (contact area) increased as the test continued. Hertzian contact pressure was calculated at the beginning. The final contact area was measured to determine the final p.s.i. load. Only the unit load on the block was recorded during the test.

TABLE III-8

RING SURFACE	BLOCK SURFACE	LOAD	CYCLES PER LOAD	TOTAL CYCLES	FINAL BLOCK TEMP	INITIAL COEFFICIENT OF FRICTION	FINAL COEFFICIENT OF FRICTION	APPROXIMATE P.S.I. SURFACE START	FINISH
BARE	*BARE*	*15 lbs.*	*<10*	*<10*		*GALLING*	*7.60*	*16,800*	*16,800*
TIODIZE II	*BARE*	*15 lbs*	*229*	*229*	*90þF*	*.40*	*7.60*	*16,800*	*16,800*
TIODIZE II-X	*BARE*	*15lbs*	*220*	*220*	*75þF*	*.07*	*.07*	*16,800*	*4,000*
		30lbs	*15,000*	*15,220*	*99þF*	*.07*	*.12*	*16,800*	*4,000*
		60lbs	*12,793*	*28,013*	*124þF*	*.10*	*.23*	*16,800*	*4,000*
TIODIZE IV	*BARE*	*15 lbs.*	*220*	*220*	*72þF*	*.05*	*.07*	*16,800*	*10,000*
		30 lbs.	*17,500*	*17,720*	*104þF*	*.07*	*.14*	*16,800*	*10,000*
		60 lbs.	*15,000*	*32,720*	*124þF*	*.14*	*.15*	*16,800*	*10,000*
		90 lbs.	*15,000*	*47,720*	*138þF*	*.12*	*.13*	*16,800*	*10,000*
		150 lbs.	*2,800*	*50,520*		*.12*	*.23*	*16,800*	*10,000*

Titanium VS Tribo/Comp IMFC-1Z Composite Bearing Material

This test was conducted on a LFW - 1 testing machine. The rotational speed was 223 rpm which equates to approximately 965 in/min. The load on the block was constantly increased to maintain approximately 20,000 p.s.i. at the ring block interface. At approximately 4,000 cycles the load was decreased to maintain a load at approximately 1,000 p.s.i. The wear rate of the bearing was determined at 20,000 p.s.i. and 1,000 p.s.i.

TABLE III-9

RING MATERIAL	BLOCK MATERIAL	NUMBER OF CYCLES	APPROXIMATE P.S.I. LOAD	WEAR RATE
TITANIUM 6 Al-4V BARE	*TRIBO/COMP IMFC-1Z*	*3,789*	*20,000*	*2.9 X 10^{-3} in/1000 sliding ft*
		13,151	*1,000*	*8.5 x 10^{-4} in/1000 sliding ft.*
TITANIUM 6Al-4V WITH TIODIZE II	*TRIBO/COMP IMFC-1Z*	*4,458*	*20,000*	*1.5 X 10^{-3} in/1000 sliding ft.*
		33,217	*1,000*	*1.0 x 10^{-4} in/1000 sliding ft.*
TITANIUM 6Al-4V WITH TIODIZE IV	*TRIBO/COMP IMFC-1Z*	*6,690*	*20,000*	*0.8 X 10^{-3} in/1000 sliding ft.*
		56,650	*1,000*	*0.5 X 10^{-4} in/1000 sliding ft.*

The test showed that using TIODIZE II compared to bare titanium would reduce wear on the bearing material by almost one half at 20,000 p.s.i. The wear rate of the bearing material was less than one eighth when using TIODIZE II compared to bare titanium at 1,000 p.s.i.

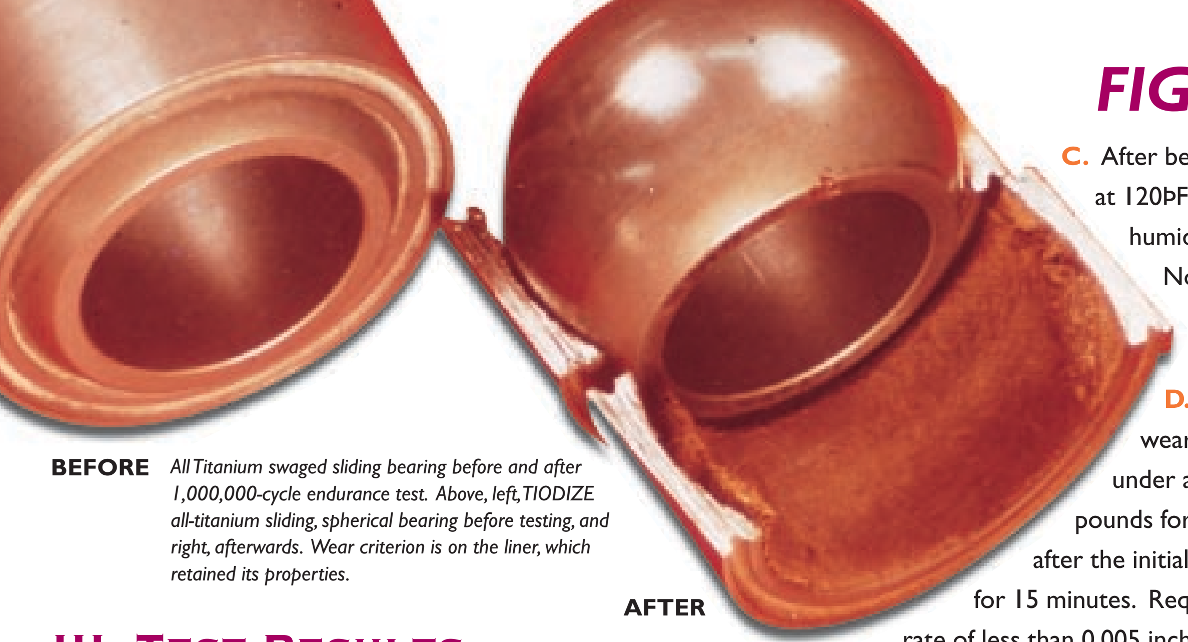


FIGURE 3-5

C. After being exposed for 96 hours at 120ÞF to 95 percent relative humidity (FTMS, Method No. 6201), three bearings shall pass the entire Test A.

D. High speed oscillation wear life test ±10Þ at 200 CPM, under a static radial load of 11,360 pounds for at least 1,000,000 cycles, after the initial radial load has been held for 15 minutes. Required criterion is a wear rate of less than 0.005 inch.

BEFORE *All Titanium swaged sliding bearing before and after 1,000,000-cycle endurance test. Above, left, TIODIZE all-titanium sliding, spherical bearing before testing, and right, afterwards. Wear criterion is on the liner, which retained its properties.*

AFTER

III. Test Results

AN ALL TITANIUM SLIDING BEARING TEST

One of the most prominent bearing manufacturers in the country was recently faced with an almost impossible dilemma: to manufacture a one inch bore spherical bearing entirely made of Ti-6Al-4V while complying with all the requirements of the MIL-B-8942 specification. This specification was originally written for self-aligning steel bearings, lubricated with a fiberglass reinforced PTFE (teflon) liner, and capable of operating with standard aircraft and hydraulic oils, and de-icing fluids.

It was also specified that re-lubrication during operational life not be permitted, and that the bearing pass the following four tests:

A. Low speed oscillating wear life test, ±25Þ at 10 CPM, under a static radial load of 34,100 pounds for at least 5000 cycles, after the initial radial load has been held for 15 minutes. Required criterion is a wear rate of less than 0.0005 inch after completion of the test.

B. After immersion for 24 hours in the following fluids at 160ÞF, three bearings shall pass the entire Test A again within 1/2 hour after removal from the following fluids:

1. Skydrol 500A Hydraulic Fluid.
2. MIL-H-5606 Hydraulic Fluid.
3. MIL-L-7808 Lubricating Oil.
4. MIL-A-8243 Anti-Icing Fluid.

The bearing manufacturer reported that his swaged Ti-6Al-4V reinforced teflon-lined bearing processed with **TIODIZE *Type II*** was the first of its kind passing this MIL-B-8942 test series. The TIODIZE® anodic coating was applied on the O.D. of the ball and on the I.D. of the cylindrical race prior to application of the teflon liner. Both areas were burnished, as shown in Figure 3-5.

The following comments by the manufacturer were made pertinent to the effects of the TIODIZE PROCESS as evidenced by the tests:

1. Swaging had no effect on **TIODIZE *Type II***; no cracking, peeling, or coating removal was observed. It should be pointed out that the coated race, after application of the liner, is swaged and formed around the ball and subsequently machined to its final dimensions.

2. To keep the liner in place during the swaging operation, it is necessary that the adhesive system exhibit a minimum peel strength of 6 pounds per inch. Routine figures, as obtained in bonding the reinforced liner to aluminum, 4340 alloy steel, and 17-4PH steel, range from 7 to 9 pounds per inch. With the TIODIZE® coated Ti-6Al-4V substrate, peel strength of the liner varied from an impressive 10 to 15 pounds per inch.

3. The most important factor in this type of endurance test is the wear effects on the ball's surface finish, usually held to 8 microinches R.M.S. After processing with **TIODIZE *Type II***, profilometer data indicated that a surface finish improvement had occurred. The burnished TIODIZE® coating resulted in a maximum surface finish of four microinches R.M.S. extending the wear life 30 percent over that required by the MIL-B-8942 specification. This resulted in a remarkably smooth ball surface, shown in Figure 3-5.

4. In addition to these observations, test results also indicated complete compatibility with the various aircraft fluids, no adverse effects from temperature exposures from -65ÞF to 250ÞF, and satisfactory performance after exposure to humidity.

III. Test Results

HYPERGOLIC FLUIDS TEST

TIODIZE PROCESS, being a completely inorganic material, is chemically compatible. After exposure to the following well-known reactive fluids, the coated Ti-6Al-4V panels did not show any adverse effects, nor was there any pressure buildup in the test tubes:

A. 70 percent nitric acid solution - 120 hours.
B. 10 percent nitric acid solution - 120 hours.
C. Nitrogen tetroxide oxidizer - 336 hours.
D. Anhydrous hydrazine fuel - 336 hours.
E. Non-methyl hydrazine fuel - 336 hours.
F. 50:50 blend of unsymmetrical dimethyl hydrazine and hydrazine - 336 hours.

Additional evaluations revealed that the TIODIZE PROCESS does not induce corrosive attack of any kind after 336 hours of exposure to a 5 percent salt spray test. Initial measurements conducted and lack of any efficient test method for coatings as thin as TIODIZE® show this material to be classified as a semi-dielectric type of material. The results obtained so far indicate an electric resistivity between 10^7 and 10^8 Ohmcentimeters on the **TIODIZE *Type I*** coating.

ROCKET PROPELLANT SEAL TEST

A quite unusual application is one where the prime objectives were galvanic corrosion protection and leakage prevention between the butyl O-Ring and a Ti-6Al-4V injector body of a 10,000 pound thrust rocke engine. The O-Ring was mounted into a 2024T4 alumir mated part which in turn was also fastened to the Ti-6A body. This assembly was used in a rocket propellant injec system consuming hydrazine-type fuels and nitrogen-tetroxide oxidizers. After TIODIZE® was applied and burnished on the Ti-6Al-4V body flange facing the O-Ring, the propellant leakage ceased and galvanic corrosion protection was provided.

Heretofore, the only other possible propellant compatible candidate material (a teflon-type sprayed-on coating) was not able to retain its leakproof properties throughout the duration of the test.

TITANIUM ACTUATOR TEST

Another interesting application was reported by the manufacturer of the actuator used in the spoiler system of a variable-wing-sweep type aircraft. The Ti-6Al-4V forged actuator body's main bore of 1.875 inch diameter accommodated a fiberglass-reinforced, teflon-cloth-covered piston which had a stroke of almost two inches. The hydraulic fluid was the MIL- H-5606 material, and Buna-N O-Rings were used on the piston. So far, this type of design could not meet the 800,000 cycle operational life requirement because the high side load caused the titanium to gall, the teflon liner to wear prematurely and the O-Rings to tear. The forged titanium actuator body is an extremely complex machined part, and, as shown in Figure 3-6, reaming and refinishing of the bore was virtually impossible, if not economically prohibitive.

After the TIODIZE® coating was applied on the bore's I.D.,

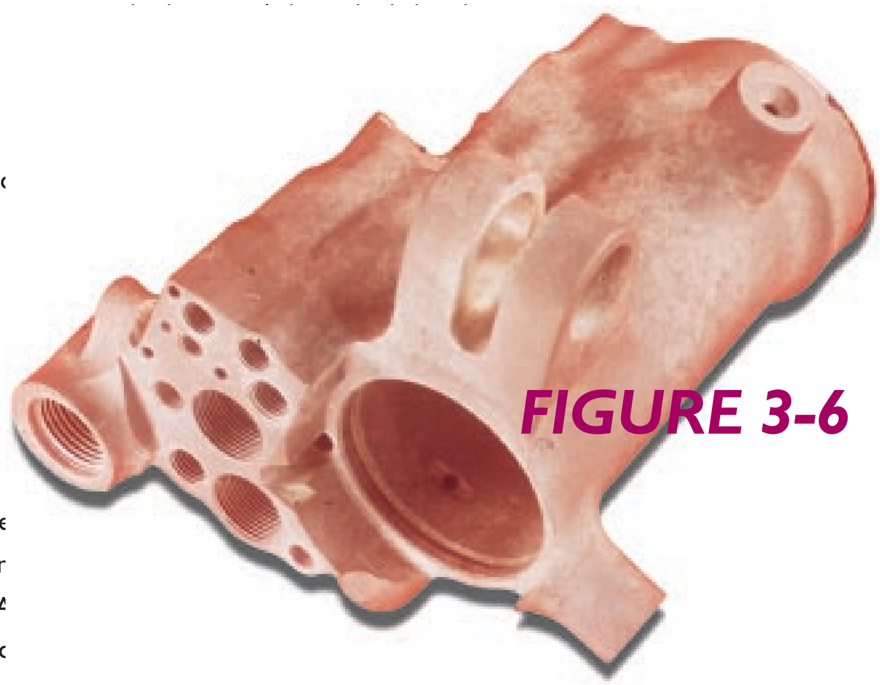


FIGURE 3-6

and loads. At the conclusion of the test, the TIODIZED bore showed only minor scratches and burnish marks. An additional test, with intermittent strokes and varying loads at 275ÞF was successfully completed after the reduced 175,000 cycles.