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**Effects of Testing and Storage Environments
on Mechanical Properties
of Ni-Plated and Bare U-3/4 wt% Ti**

MASTER

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EFFECTS OF TESTING AND STORAGE ENVIRONMENTS ON
MECHANICAL PROPERTIES OF NI-PLATED AND BARE U-3/4 WT% TI

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ABSTRACT

A series of statistically designed experiments was used to study the effects of test and storage environments on the mechanical properties of bare and plated U-3/4% Ti alloy. The major variables examined were surface condition, tensile testing environment, strain rate, storage environment, and storage time. The observed absence of catastrophic moisture corrosion of bare samples during storage can be attributed to the presence of an adequate O₂ supply, which decreases the reaction rate with moisture. Testing environments favorable to the formation of corrosion-initiated surface cracks caused premature failure during testing and the observed ductility degradation. Strength was found to increase with increasing strain rate and lower test temperature. Nickel plating caused a decrease in tensile strength but not ductility, while the presence of high explosive had no effect on mechanical properties.

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EFFECTS OF TESTING AND STORAGE ENVIRONMENTS ON MECHANICAL PROPERTIES OF NI-PLATED AND BARE U-3/4 WT% TI

Introduction

It has been known for some time that both the testing and storage environments^{1,2} can have an effect on the mechanical properties of uranium alloyed with titanium. Storage of bare, quenched, and aged U-3/4 wt% Ti in 100% relative humidity (RH) environments can lead to significant ductility loss^{1,2} and high rates of H₂ generation (e.g., $\sim 10^{-2}$ moles/m²-day in wet O₂ and $\sim 10^{-1}$ moles/m²-day in wet N₂).² This H₂ generation is accompanied by formation of visible quantities of solid corrosion product. Nickel/zinc plating has been shown to be an effective means of mitigating the corrosion,³ but significant ductility losses have still occurred when the plated specimens were pulled slowly in a moist, room-temperature environment.^{1,4}

In storage tests by Weirick,⁵ plated and bare U-3/4 wt% Ti disks were adhesively bonded to LX-10 high explosive with silastic DC 93-119.* Bare specimens were sealed in containers with dry air (1 ppm H₂O at 23°C) and plated samples with 60% RH (at 20°C) air before storing both at 70°C. Analysis of the atmosphere of one of the containers for the bare specimen after three months of storage showed virtually complete removal of the O₂ (< 0.25%) and an accompanying buildup of H₂ to about 40% of the total gas in the container. There was also visual evidence of large amounts of corrosion product at the silastic/U-3/4 wt% Ti interface. For those U-3/4 wt% Ti samples plated with 25-50 μ m of Ni and stored under the same conditions, the O₂ level in the containers was found to be only moderately reduced and there was negligible evidence of H₂ generation or solid corrosion product formation. While Weirick measured no mechanical properties for these disk specimens, considerable concern developed that prolonged association of bare U-3/4 wt% Ti with LX-10 could lead to the type of ductility loss found earlier for specimens stored in high-humidity environments.² There has been further concern, because of a history of large unexplained scatter in the ductilities of plated U-3/4 wt% Ti tensile samples, that the plating process itself might occasionally and unpredictably contribute to the ductility loss phenomenon, independent of the storage and testing environment histories.

*Product of Dow Corning.

The present work is a further examination of these concerns using statistical design techniques to study the effects of storage and testing environments, with and without LX-10, on the mechanical properties of bare and plated U-3/4 wt% Ti.

Experimental Procedure

Test Plan and Variables Examined

Tensile tests were performed on two groups of samples to separate the effects of mechanical test environment from those of storage environment. The samples for assessing test environment effects were not stored before being tested. For the other group of stored samples, all testing was done in vacuum at room temperature (RT). Each group was tested according to a two-level factorial experimental design^a involving the variables summarized in Table I. Tensile properties were measured on at least two specimens subjected to each combination of test conditions, and the results were analyzed for the presence of significant mechanical property effects using standard statistical procedures.^b

TABLE I
SUMMARY OF TEST VARIABLES FOR U-3/4 TI TENSILE BARS

Variable	Level ^a	
	(-)	(+)
<u>Group I--Tensile Testing Environment Effects</u>		
Surface Condition	Bare	Plated ^b
Test Environment	Vacuum	100% RH Air
Test Temperature (°C)	-34	22
Strain Rate (sec ⁻¹)	5×10^{-4}	1.0
<u>Group II--Storage Environment Effect (room-temperature mechanical testing done in vacuum)</u>		
LX-10	Absent	Present ^c
Surface Condition	Bare	Plated ^b
Storage Temperatures for 30 weeks (°C)	50	70
Storage Times @ 70°C (wk)	10	30
Strain Rate (sec ⁻¹)	10^{-3}	1.0

^a Experimental design strategy calls for testing at two extreme conditions, labeled "-" and "+." See Reference 6 for details.

^b The plating consisted of 25 µm Ni + 5 µm chromated Zn.

^c "LX-10 present in storage chamber" involves U-3/4 Ti specimens sandwiched into grooves machined in the LX-10 blocks but contacting a painted-on precured layer of Halthane 73-18 rather than LX-10 directly.

Alloy Processing and Specimen Fabrication

The U-3/4 Ti alloy used was taken from a single ingot (produced at Union Carbide's Y-12 plant) having a typical Ti content of 0.8 wt%. This material was back-extruded into hollow cylinders having a wall thickness of approximately 2 cm. These cylinders were then solution treated in vacuum for four hours at 800°C, water quenched, and aged in vacuum for six hours at 380°C. The quenched cylinders were cut into machining blanks from which either button head or threaded tensile specimens were fabricated. The gage diameter and gage length were 6.4 mm and 25.4 mm, respectively, for all specimens.

Plating

Those specimens which were to be plated were first etched in 1400-g/l ferric chloride. This removed about 25 μm of metal from the surface. The parts were then plated with 25 μm of nickel plus 5 μm of zinc, which was then chromated. Full details of the etching and plating procedures are included in Appendix A.

Mechanical Testing

The test apparatus consisted of an MTS mechanical testing machine fitted with an environmental chamber capable of maintaining either 10^{-6} torr or 100% RH air at the chosen test temperatures of 22°C or -34°C. Photographs showing details of the test apparatus appear in Figures 1 and 2.

Yield strengths and ultimate tensile strengths were calculated from the load-deflection curves recorded for each test. Elongation was measured by an extensometer and checked by gage marks scribed on the specimens before pulling. Reduction-in-area measurements were determined with the aid of a shadowgraph.

Storage Environments

Stainless steel containers equipped with gas sampling ports were used for storing specimens (Figure 3). Half the stored tensile bars were sealed in these vessels in an atmosphere of lab air ($\sim 20\%$ RH at 20°C) with no other materials added. The remainder of the stored specimens were inserted into blocks of the high explosive (HE) LX-10 (94.5% HMX/5.5% Viton A) machined with grooves to accept the specimens (Figure 4). The specimens were in direct contact with a polyether polyurethane adhesive, Halthane 73-18, which had been painted into the grooves and allowed to cure before emplacement of the tensile bars. The two halves of the HE block were held together with a strip of aluminum foil. Two tensile bars of each surface condition (bare or

Figure 1. Mechanical Testing Equipment

Figure 2. Test Setup Inside of Vacuum Chamber

plated) were subjected to each combination of storage environment, temperature, time, and (later) tensile strain rate. Just before opening the containers for specimen removal, gas samples were withdrawn for mass spectrometric analysis.

Figure 3. Schematic, Container for Storing Specimens

Figure 4. Configuration for Exposure of U-3/4 wt% Ti to LX-10

Fractography and Metallography

After tensile testing, the fracture surfaces and other visual features of representative specimens were examined by optical microscopy and scanning electron microscopy (SEM). Selected specimens were also sectioned and examined metallographically for the purpose of correlating microstructural variations with otherwise unexplained variations in mechanical properties.

Statistical Analysis

The mechanical properties measured for both groups of specimens were subjected to standard statistical analysis to determine which of the storage and test variables had significant influence on ductility and strength. An example of this type of analysis appears in Appendix B. A full explanation of the statistical procedure can be found in any of several treatments of experimental design strategy.⁷

Results

Mechanical Properties

Test Condition Effects. The measured values of yield strength (YS), ultimate tensile strength (UTS), % elongation (%EL) and reduction in area (RA) for the unstored specimens tested under various conditions are summarized in Table II. The details of the statistical analyses appear in Appendix B. Tables B.I-B.IV show the results of these analyses. The statistical significance of the various test variables on each of the measured properties is summarized in Table III. As can be seen from this summary, ultimate tensile strength is sensitive to test temperature, test environment, and strain rate but not to surface condition; elongation is sensitive to the temperature and environment, and insensitive to strain rate. However, there was a marked effect of strain rate on RA: necking was much more pronounced at high strain rate than at low.

Storage Effects. The measured values of YS, UTS, %EL, and RA for the stored specimens are recorded in Tables IV-VII. The statistical significance of the variations in the storage factors for each of these properties is summarized in Table VIII. This table shows that none of the storage factors examined had a significant effect on the average ductility as measured by %EL or RA. It also indicates that there were statistically significant effects on UTS due to plating and on YS due to variation in storage time at 70°C and strain rate. The magnitudes of these strength differences are probably too small to be of practical design importance.

TABLE II

SUMMARY OF MECHANICAL PROPERTIES OF U-3/4 T1 TESTED UNDER VARIOUS CONDITIONS^a

Surface and Test	Strain Rate (sec ⁻¹)	Yield Strength ^b 0.2% Offset		UTS		Elongation (%)	RA (%)
<u>Bare</u>		(MN/m ²)	(KSI)	(MN/m ²)	(KSI)		
RT, vacuum	5 x 10 ⁻⁴ 1.0	821	119	1483	215	20.5	15
		-	-	1524	221	13.4	28.0
RT, 100% RH	5 x 10 ⁻⁴ 1.0	945	137	1117	162	2.0	1.7
		-	-	1530	221.8	10.8	15.7
-34°C, vacuum	5 x 10 ⁻⁴ 1.0	979	142	1538	223	7.3	6.0
		-	-	1614	234	5.0	3.3
-34°C, 100% RH	5 x 10 ⁻⁴ 1.0	965	140	1485	216	5.6	4.3
		-	-	1593	231	7.7	5.3
<u>Plated</u>							
RT, vacuum	5 x 10 ⁻⁴ 1.0	876	127	1476	214	19.2	16
		-	-	1483	215	15.5	27.5
RT, 100% RH	5 x 10 ⁻⁴ 1.0	945	137	1400	203	5.3	5.1
		-	-	1469	213	16.0	25.9
-34°C, vacuum	5 x 10 ⁻⁴ 1.0	979	142	1448	210	3.8	2.5
		-	-	1551	225	6.4	4.2
-34°C, 100% RH	5 x 10 ⁻⁴ 1.0	938	136	1627	236	6.6	4.6
		-	-	1552	225	6.8	5.0

^aResults are averages of at least 2 specimens.^bYield strength could not be accurately determined at high strain rate.

TABLE III

STATISTICALLY SIGNIFICANT EFFECTS OF TEST CONDITIONS ON MECHANICAL PROPERTIES

Test Variable	Yield strength	Ultimate Tensile Strength	Elongation	Reduction in area
Surface Condition	NE ^a at low ϵ	NE	NE	Higher bare
Test Environment	Higher in vacuum	Higher in vacuum	Higher in vacuum at RT and low ϵ NE at low temperature	Higher in vacuum
Test Temperature	Higher at low temperature	Higher at low temperature	Lower at low temperature	Lower at low temperature
Strain Rate $\dot{\epsilon}$	Not measured in higher strain rate	Higher at high strain rate	NE	Greater at high strain rate at RT. No significant difference at low temperature
No effect				

TABLE IV

MECHANICAL PROPERTIES AT LOW STRAIN RATE^a OF U-3/4 Ti STORED FOR 10 WEEKS AT 70°C

Sample History	Yield Strength 0.2% Offset		Ultimate Tensile Strength		% Elongation in 1.0 inch	% Reduction in Area	Remarks
	(MN/m ²)	(ksi)	(MN/m ²)	(ksi)			
<u>Controls^b</u>							
C-4 Bare	960	139.3	1480	214.6	23.2	21.1	c
C-13 Plated	939	136.1	1381	200.2	16.0	13.4	c
C-15 Plated	941	136.4	1337	193.9	9.1	8.2	c
10-3 Bare	976	141.5	1484	215.2	20.0	27.7	d
10-4 Bare	963	139.7	1487	215.7	24.4	28.5	d
3-4 Plated	956	138.7	1405	203.8	19.6	28.1	d
<u>With LX-10</u>							
21-3 Bare	970	140.6	1447	209.9	18.3	22.9	d
21-4 Bare	978	141.8	1478	214.3	22.7	23.9	d
15-4 Bare	947	137.4	1430	207.4	18.3	14.2	d

^aTested in vacuum at room temperature with a strain rate of 10^{-3} sec⁻¹.^bWhere two numbers are given, first number refers to container number at Pantex.^cStored at RT at SLL.^dStored at Pantex.

TABLE V

MECHANICAL PROPERTIES AT HIGH STRAIN RATE^a OF U-3/4 T1 STORED FOR 10 WEEKS AT 70°C

Sample History	Yield Strength 0.2% Offset		Ultimate Tensile Strength		% Elongation in 1.0 inch	% Reduction in Area	Remarks
	(MN/m ²)	(ksi)	(MN/m ²)	(ksi)			
<u>Controls^b</u>							
C-3 Bare	1010	146.5	1459	211.5	19.2	22.2	c
C-14 Plated	995	144.3	1407	204.0	17.1	35.2	c
C-17 Plated	988	143.3	1424	206.5	17.8	20.5	c
9-1 Bare	1007	146.0	1451	210.4	19.6	22.0	d
9-2 Bare	990	143.6	1444	209.4	15.6	23.7	d
4-2 Plated	1043	151.2	1476	214.0	14.4	23.7	d
3-3 Plated	1092	158.4	1421	206.1	17.3	24.7	d
<u>With LX-10</u>							
22-1 Bare	1143	165.7	1497	217.1	15.0	28.9	d
22-2 Bare	1019	147.8	1456	211.1	17.5	23.9	d
16-1 Plated	1057	153.4	1492	216.4	17.7	22.6	d
16-2 Plated	1080	156.6	1463	212.9	8.0	7.3	d
15-3 Plated	950	137.8	1404	203.6	17.6	26.4	d

^aTested in vacuum at room temperature with a strain rate of 1.0 sec⁻¹.^bWhere two numbers are given, first number refers to container number at Pantex.^cStored at RT at SLL.^dStored at Pantex.

TABLE VI

MECHANICAL PROPERTIES AT LOW STRAIN RATE^a OF U-3/4 T1 STORED FOR 30 WEEKS AT 50°C and 70°C

Sample History	Yield Strength 0.2% Offset		Ultimate Tensile Strength		% Elongation in 1.0 inch	% Reduction in Area	Remarks
	(MN/m ²)	(ksi)	(MN/m ²)	(ksi)			
Controls^b							
C-2 Bare ^c	1063	154.2	1400	203.0	5.4	5.3	d
C-12 Plated	1013	146.9	1386	201.1	17.4	15.3	d
C-18 Plated	1037	150.4	1383	200.5	15.0	14.6	d
7-2, 50° Bare	1063	154.1	1475	213.9	22.2	30.6	e
8-2, 50° Bare ^c	1049	152.1	1368	198.4	8.9	8.5	e
1-2, 50° Plated	1031	149.5	1417	205.5	21.0	27.7	e
2-2, 50° Plated	1026	148.8	1409	204.3	22.0	26.1	e
11-2, 70° Bare ^c	1087	157.7	1496	216.9	14.3	13.5	e
12-2, 70° Bare	1065	154.5	1483	215.1	23.4	28.4	e
5-2, 70° Plated ^c	1073	155.6	1452	210.6	10.4	9.6	e
6-2, 70° Plated	1034	150.0	1426	206.9	19.6	25.4	e
LX-10							
19-2, 50° Bare	1051	152.5	1468	213.0	23.4	30.2	e
20-2, 50° Bare ^c	1063	155.0	1474	213.8	12.6	9.6	e
13-2, 50° Plated	1054	152.8	1416	205.0	18.4	28.5	e
14-2, 50° Plated ^c	1090	158.0	1471	213.4	11.3	7.5	e
23-2, 70° Bare	1090	158.0	1530	222.1	20.0	23.8	e
24-2, 70° Bare	1094	158.7	1507	218.6	17.3	29.5	e
17-2, 70° Plated	-	-	1434	208.0	13.6	26.1	e
18-2, 70° Plated	1050	152.3	1424	206.5	21.3	27.7	e

^aTested in vacuum at room temperature with strain rate of 10⁻³ sec⁻¹.^bWhere two numbers are given, first number refers to container number at Pantex.^cSuspected bad heat treatment.^dStored at room temperature at SLL.^eStored at Pantex.

TABLE VII

MECHANICAL PROPERTIES AT HIGH STRAIN RATE^a U-3/4 Ti STORED FOR 30 WEEKS AT 50°C and 70°C

Sample History	Yield Strength 0.2% Offset		Ultimate Tensile Strength		% Elongation in 1.0 inch	% Reduction in Area	Remarks
	(MN/m ²)	(ksi)	(MN/m ²)	(ksi)			
<u>Control Samples^b</u>							
C-1 Bare	1269	184.0	1544	224.0	16.1	19.2	c
C-11 Plated	1187	172.2	1420	206.0	13.0	23.5	c
C-16 Plated	1043	151.3	1388	201.3	15.8	22.0	c
7-1, 50° Bare	1104	160.1	1488	215.7	11.6	33.7	d
8-1, 50° Bare	--	--	1503	218.0	11.0	22.2	d
1-1, 50° Plated	858	124.5	1422	206.3	12.7	25.3	d
2-1, 50° Plated	1062	154.0	1420	206.0	16.4	20.9	d
11-1, 70° Bare	--	--	1451	210.4	14.8	20.1	d
12-1, 70° Bare	1101	159.7	1501	217.7	13.6	20.4	d
5-1, 70° Plated	1328	192.6	1485	215.4	11.2	11.5	d
6-1, 70° Plated	1055	153.0	1422	206.2	17.0	24.1	d
<u>LX-10 Sample</u>							
19-1, 50° Bare	1120	162.5	1516	219.9	14.1	23.0	d
20-1, 50° Bare	1109	160.8	1524	221.0	13.4	22.3	d
13-1, 50° Plated	--	--	1412	204.8	16.8	24.7	d
14-1, 50° Plated	1105	160.2	1462	212.1	16.6	16.2	d
23-1, 70° Bare	1133	164.3	1512	219.3	17.2	23.8	d
24-1, 70° Bare	1108	160.8	1517	220.1	18.0	22.9	d
17-1, 70° Plated	1051	152.4	1417	205.5	20.8	31.7	d
18-1, 70° Plated	1068	155.0	1425	205.7	19.8	25.4	d

^aTested in vacuum at room temperature with a strain rate of 1.0 sec⁻¹.^bWhen two numbers are given, first number refers to container number at Pantex.^cStored at RT at SLL.^dStored at Pantex.

TABLE VIII

STATISTICALLY SIGNIFICANT EFFECTS OF STORAGE CONDITIONS ON MECHANICAL PROPERTIES(a)

Test Variable	Yield Strength	Ultimate Tensile Strength	Elongation	Reduction in Area
Environment	NE ^b	NE	NE	NE
Surface	Greater for bare at low ϵ , NE at high ϵ	Greater for bare	NE	NE
Storage Temp	NE	NE	NE	NE
Storage Time	Greater for longer times	NE	NE	NE
Strain Rate	NE	Higher for high strain rate	NE	NE

Other Variables Non-uniform cooling rate through the thickness of the quench billet led to variable aging response among the samples. This produced a rather larger scatter in all mechanical properties which tended to obscure the effects of the storage variables of interest.

^aTensile testing done in 10^{-6} Torr vacuum at room temperature.

^bNo effect.

Gas Analysis of Storage Environments. In Table IX the measured compositions of storage chamber atmospheres from the current tests and Weirick's⁵ are presented for comparison. Of particular significance are the trends in O₂ concentration with storage time and temperature. For both series of tests where bare U-3/4 Ti was stored at 70°C, there was a decrease in O₂ content with increasing storage time. The rate of O₂ decrease per U-Ti surface area was similar in both tests (Table X), although the total O₂ content of Weirick's containers was less. For Weirick's three-month test, the O₂ was virtually gone, while for our 30-week storage period less than half the original O₂ was consumed. In agreement with Magnani's⁶ finding that O₂ reduces the reduction rate, Weirick's three-month test exhibited a high H₂ content, reaching ~ 40 vol-%, while it was a rather insignificant fraction of the total atmosphere for the current tests. In agreement with the quantities of H₂ found, Weirick's U-3/4 Ti disk exhibited extensive corrosion while the tensile bars aged in this study showed only a dark tarnish film.

Microstructure

The microstructures of the U-3/4 Ti specimens in the current test series were typical of those reported by Eckelmeyer⁸ for this alloy in the quenched and aged condition. There was evidence that some samples had too slow a quenching rate during heat treatment prior to aging. This is indicated by the presence of martensite-free borders along prior gamma grain boundaries.¹⁰ In Figure 5 an extreme example of this bordered microstructure is contrasted with an example of an "adequately" quenched microstructure which has entirely transformed to martensite. The elongations of these two samples were 5.4% and 12.6%, respectively. Examination of the microstructure of a large number of other samples revealed a moderate correlation between the degree of "bordering" and lowered ductility, but there were many exceptions. In most cases, a moderate correlation was found between the larger prior gamma grain size and lower specimen ductility, but not always. These microstructural factors, even taken together, are not enough to account for all of the large scatter found in ductility values for these tensile bars.

Fractography

The fracture morphologies of these samples were also typical of those frequently reported in the past for this alloy with this heat treatment.^{1,10} On the fracture surfaces of all samples examined there were regions of dimple rupture intermixed with areas of quasi-cleavage fracture which reflected the orientation of the underlying martensite. Representative scanning electron microscope (SEM) micrographs of this mixed mode fracture appear in Figure 6. SEM or optical examination at low magnification (10-100x) invariably showed the fracture origin at or near the surface for specimens with comparable RA and %EL values (i.e., little necking). For those specimens with

(a) Sample 20-2 (150x)

(b) Sample C-2 (150x)

Figure 5. Examples of (a) Adequately and (b) Inadequately Quenched U-3%Ti

300x

1000x

Figure 6. Typical Fracture Mode; Sample No. 2, Unplated

appreciable necking, the fracture origins were always located well into the specimen interiors. Examples of the morphologies for these two types of fracture initiation appear in Figure 7.

**Surface origin of
fracture (50x)**

**Internal fracture
origin (large shear
lips are evident
around the specimen
periphery) (50x)**

Figure 7. Two Types of Fracture

TABLE IX

COMPARISON OF GAS ANALYSES FOR STORAGE ENVIRONMENTS IN WEIRICK'S³ AND CURRENT TESTS

Gas Species (vol %)*	Weirick's Tests					Current Tests									
	70°C, HE present					70°C									
	1 mo		3 mo		2 mil Ni plate	10 Wk				30 Wk				50°C 30 Wk	
	WR	Bare	Bare	1 mil Ni plate		HE	Plated	No HE		HE	Plated	No HE		HE	No HE
						Bare	Plated	Bare	Plated	Bare	Plated	Bare	Plated	Bare	Plated
H ₂	-	.56	40.31	.25	.06	.04	.05	-	-	-	-	-	.04	-	.02
O ₂	21	13.43	.23	14.82	15.06	19.0	20.6	19.2	20.8	13.2	20.3	16.2	20.3	20.2	20.6
CO ₂	.03	1.50	.86	2.48	2.50	.13	.14	.13	.07	.28	.23	.15	.12	.11	.10
CH ₄	-	-	-	-	-	.04	.05	-	-	-	-	-	.04	-	.02
N ₂ O	-	2.79	3.45	7.44	6.28	.14	-	-	-	.07	.08	-	-	-	-
H ₂ O	-	.79	<.02	.09	.21	-	-	-	-	-	-	-	-	-	-
Acetone	-	.35	.11	.06	.15	.12	.14	-	-	.13	.15	-	-	.10	.08
N ₂	78.39	79.52	54.1	73.62	74.71	79.7	77.6	79.7	78.1	85.1	78.3	82.4	78.6	78.7	78.3
Ar	.94	.94	.62	.88	.89	.96	.92	.96	.94	1.0	.92	.98	.93	.92	.92
CO	-	-	.24	.28	-	-	-	-	-	-	-	-	-	-	-
Other	.03	.12	.06	.06	.15	-	-	-	-	-	-	-	-	-	-

*Free volume in Weirick's chamber: 33 cm³.Free volume in current tests: No HE present - 269 cm³; with HE present - 232 cm³.

TABLE X

PARAMETERS USED FOR CALCULATION OF O_2 /BARE U-Ti OXIDATION RATE DURING STORAGE IN AIR WITH AND WITHOUT HE PRESENT

	HE Present	Storage Temperature (°C)	Storage Periods (days)	Initial moles O_2	Total moles O_2 Consumed	Free Volume of Storage Container (cm^3)	Reacting U-Ti Surface Area (cm^2)	Reaction Rate (moles O_2/cm^2 -day)
Current tests:	Yes	50°C	210	1.98×10^{-3}	7.54×10^{-5}	232.1	49.5	7.26×10^{-9}
U-Ti tensile	No	50°C	210	2.29×10^{-3}	7.63×10^{-5}	269	49.5	7.34×10^{-9}
bars, two per	Yes	70°C	210	1.98×10^{-3}	7.35×10^{-4}	232.1	49.5	7.07×10^{-8}
container	No	70°C	210	2.29×10^{-3}	5.23×10^{-4}	269	49.5	5.04×10^{-8}
	Yes	70°C	70	1.98×10^{-3}	1.89×10^{-4}	232.1	49.5	5.44×10^{-8}
	No	70°C	70	2.29×10^{-3}	1.96×10^{-4}	269	49.5	5.67×10^{-8}
Weirick tests:								
U-Ti disks,	Yes	70°C	28	2.82×10^{-4}	1.01×10^{-4}	33	91	3.98×10^{-8}
total area	Yes	70°C	84	2.82×10^{-4}	2.79×10^{-4}	33	91	3.64×10^{-8}
assumed to								
react								
Weirick tests	Yes	70°C	28	2.82×10^{-4}	1.01×10^{-4}	33	53.4	6.78×10^{-8}
U-Ti, disks,	Yes	70°C	84	2.82×10^{-4}	2.79×10^{-4}	33	53.4	6.21×10^{-8}
37.6 cm^2								
coated with								
silastic assumed								
not to react								

Secondary Surface Cracks

Microscopic examination of the machined surfaces of the specimen gage sections commonly revealed multiple nonfatal secondary cracks in those specimens which ultimately failed without appreciable necking. Figure 8 shows a series of micrographs with typical secondary cracks. These pictures are from a bare specimen, pulled at 10^{-3} sec $^{-1}$ in vacuum, which broke at 12.6% elongation. The specimen had been stored 30 weeks at 50°C in contact with LX-10 before testing. As is evident in the 100x view of Figure 8, these cracks closely followed existing machining marks and surface scratches. Such cracks are not apparent on those specimens which either broke with $\leq 7\%$ elongation or had cracking initiate in the interior. The nickel plating on tensile bars did not allow the observation of possible secondary surface cracks.

Discussion

Testing Environment Effects

Ductility Losses. Variations in test temperature, strain rate, surface condition, and humidity of the test environment all had significant effects on the RA-defined ductility. These results can be conveniently viewed as being the net outcome of the parallel operation of competing moisture corrosion, deformation, and fracture processes during testing. The severity of moisture corrosion accompanying tensile loading strongly affects the fracture behavior of the U-3/4 Ti alloy. Where conditions favor corrosion--i.e., moderate temperatures, low strain rates, and high humidity--multiple surface cracks develop during straining which eventually convert the originally smooth tensile bars into "precracked" specimens. This trend proceeds even in the presence of O₂ over the range of strain rates examined here. The continued straining apparently prevents effective repassivation while sustaining the local reaction of moisture condensed in the cracks with the freshly exposed metal at the propagating crack tips. The first of these cracks to reach critical size (in the fracture-toughness sense, as determined by the local geometric constraint and metallurgical state) propagates catastrophically, causing ultimate specimen failure.

At low temperature (-34°C) the moisture reaction is too sluggish to be important over the examined range of strain rates. The observed low ductility at low temperature is simply due to a scarcity of active slip and twinning systems, a situation little influenced by the strain rates normally used. It is well documented that the deformation mechanisms in α -uranium and its lean orthorhombic alloys are particularly sensitive to test temperature,¹¹ and such metallurgical factors as aging treatment and prior γ grain size.¹² In contrast, at room temperature in a humid test environment, a high strain rate is crucial

→ Tensile Direction

→ Tensile Direction

→ Fracture Surface

→ Tensile Direction

Figure 8. Secondary Surface Cracks

to overcome the detrimental effects of the corrosion reaction and provide the observed improvement in room temperature ductility (particularly RA) with increasing strain rate.

When moisture is absent during room temperature testing, the ultimate fractures are no longer surface nucleated by the moisture reaction, and there is no evidence of the extensive secondary surface cracking. The fracture processes under these conditions are essentially those of classic dimple rupture; i.e., the nucleation and growth of internal voids in the necked region of the specimen.

Microstructural factors alone cannot adequately account for all the large scatter found in ductility values for tensile bars. It is speculated that loss of ductility may be due to residual chloride contamination on specimen surfaces, which accelerates the moisture corrosion reaction. This speculation is supported by observed ductility improvements when a chloride ion getter such as Hg^{+} is added to a chloride-containing aqueous solution surrounding U-3/4 wt% Ti tensile bars during slow straining at room temperature.¹³

Strength Increase. Either reducing the test temperature or increasing the strain rate for room-temperature testing raises the entire flow curve for U-3/4 Ti. The increased strength at low temperature is another manifestation of the reduction in available deformation processes with decreasing temperature. This tendency also results in a higher rate of work hardening at lower temperature. These effects can be seen in Figure 9 where equivalent load-deflection curves from tests at room temperature and -34°C are compared. The higher room-temperature strength at high strain rate may be a consequence of suppressing time-dependent stress-relaxation mechanisms under conditions of high strain-rate testing. This possibility was not directly examined in this work.

Figure 9. Comparison of Load-Deflection Curves for Room-Temperature and -34°C Testing

Storage Environment Effects

O_2 Inhibition of Moisture Corrosion. The apparent contradictory evidence regarding catastrophic moisture corrosion during storage becomes self-consistent when correlated with O_2 concentrations measured at the end of the storage period: In Weirick's three-month test where catastrophic moisture corrosion was observed, there was less than 0.2 vol-% of O_2 remaining in the storage container. In all the others at least 13% O_2 remained and there was no sign of moisture corrosion. This correlation is consistent with the well-documented finding that O_2 provides effective corrosion inhibition for U alloys not being strained.²

Weirick has suggested¹⁴ that the presence of O_2 at the end of the storage period between the present experiments and his core sample is responsible for the observed difference in moisture corrosion behavior between the present experiments and his core sample. This suggestion

is well supported by subsequent detailed calculations of expected $O_2/U-3/4$ Ti reaction rate involving the appropriate values for free volume, storage time, temperature, and alloy specimen surface area. (See Appendix C for calculation details.) Not only are the calculated rates from the individual tests at 70°C self-consistent, but when combined with the calculated rates for the 50°C storage tests and literature data where rates were measured at 105°C¹⁵ a single activation energy of 16.8 kcal/mole is found to represent all cases. This activation energy is in excellent agreement to that reported by Baker and Bingle for oxidation of uranium between 300 and 450°C.¹⁶ On the basis of these calculations we estimate that 0.75 cm³ of air at 1 atm supplied initially for each cm² of alloy surface will protect it from enhanced moisture corrosion for 20 years at 25°C without replenishment. The analysis is based on the following:

1. We assumed that the $O_2/U-3/4$ Ti reaction is linear (constant rate during the entire period), as has been previously reported.¹⁵
2. We assumed that the entire specimen surface area was available for reaction in our storage tests. As limiting cases, we assumed that for Weirick's tests either (1) the entire surface area was reacting or (2) only the fraction of specimen surface not coated with silastic was available for reaction.
3. With these assumptions, the gas analysis data, the known free volumes of the storage containers, and the specimen surface areas given in Table X, reaction rates were calculated for all tests involving unplated alloy samples.
4. The rates for tests at both 50 and 70°C were combined with an earlier reported rate at 105°C in flowing 10% RH air to obtain an Arrhenius plot. The resulting activation energy of 16.8 kcal/mole is identical with the value reported by Baker and Bingle¹⁶ for the reaction at 300°C.

The results of these calculations and comparisons are summarized in Table X and in the reaction rate vs $1/T$ plot of Figure 10.

There is a persuasive self-consistency in these results, but further support could be quickly obtained from additional storage tests in which the initial O_2 supply is deliberately reduced or eliminated.

Strength Enhancement with Time. The statistical analysis revealed a small unexpected, but apparently real, trend for the UTS of stored specimens. Ultimate tensile strength increases systematically with the length of storage time at 70°C for specimens that had not been plated before storage. The data are summarized in Table XI. They represent the averages of eight specimens for each condition.

Figure 10. Arrhenius Plot for U-Ti Oxidation Data from Several Sources

TABLE XI

COMPARISON OF ULTIMATE TENSILE STRENGTHS
AMONG SPECIMENS STORED AT 70°C

Surface Condition	Storage Time at 70°C			
	10 weeks		30 weeks	
	<u>MN/m²</u>	<u>ksi</u>	<u>MN/m²</u>	<u>ksi</u>
Bare	1468	212.9	1489	217.5
Plated	1434	208	1434	208

Examination of a typical gage length cross section of a bare specimen (Figure 11) shows localized heavy deformation adjacent to the machined surface. During the plating process, this surface material was removed by the etching operation. The presence of a heavily cold-worked structure could enhance aging kinetics, and it is suggested that low-temperature aging occurs on the surface of the bare specimens during storage and contributes to the observed strength increase with storage time.

As-machined
surface

Figure 11. Machined Specimen Showing Cold Worked Surface

Conclusions

1. Storage environments with an adequate supply of oxygen can effectively minimize moisture corrosion of bare U-3/4 Ti. In particular, 0.75 cm^3 of dry air is calculated to protect 1 cm^2 of U-3/4 Ti for 20 years storage at room temperature.
2. Consideration of the geometric details of U-3/4 Ti alloy specimens and the free volumes of air (and hence O_2) available can satisfactorily explain discrepancies in corrosion behavior between recent tests and previously reported data.

3. The storage environment at 70°C produces a minor strength increase in bare samples with increasing time.
4. Decreases in ductility are observed for testing conditions of low temperature, low strain rate, and/or high humidity.
5. Surface cracks occur under the same conditions conducive to corrosion, i.e., moderate temperatures, low strain rates, and high humidity.
6. Significant increases in strength result under low-temperature and high-strain-rate conditions of tensile testing.
7. We speculate that residual chloride contamination may be responsible for the occasional and otherwise unexplained large scatter in ductility for nominally similar specimens and test conditions.
8. Nickel plating is observed to cause a statistically significant decrease in tensile strength, but no effect on the yield strength or ductility was observed.
9. The presence of high explosive during the aging of tensile bars was observed to have no effect on mechanical properties.

APPENDIX A--DETAILS OF PLATING PROCEDURES

TABLE A-I
ETCHING AND PLATING PROCEDURES

-
1. Vapor degrease in trichloroethylene.
 2. Caustic soak for 5 minutes at 70° to 80°C.
 3. Water rinse.
 4. Scrub surfaces with pumice.
 5. Water rinse.
 6. Pickle in 35 percent (by weight) solution of nitric acid at room temperature for 2 minutes.
 7. Water rinse.
 8. Etch with 1400 g/l ferric chloride solution for 10-15 minutes at 55°C.
 9. Water rinse.
 10. Pickle in 35 percent (by weight) solution of nitric acid at room temperature for 2 minutes.
 11. Water rinse.
 12. Caustic soak for 5 minutes at 70° to 80°C.
 13. Water rinse.
 14. Pickle in 35 percent (by weight) solution of nitric acid at room temperature for 2 minutes.
 15. Water rinse.
 16. Electroplate in nickel sulfamate solution (see Table A-II).
 17. Water rinse.
 18. Electroplate in zinc plating solution (see Table A-III).
 19. Water rinse.
 20. Chromate zinc plating (see Table A-IV).
 21. Water rinse.
-

TABLE A-II
NICKEL SULFAMATE SOLUTION

Nickel sulfate	450 g/l
Boric acid	30 g/l
Surface tension	34-38 dynes/cm
pH	3.80-4.0
Temperature	48° to 50°C
Anodes	Sulfur depolarized nickel
Filtration	Continuous
Current density	270 A/m ²

TABLE A-III
ZINC PLATING SOLUTION

Zinc Chloride	100 g/l
Ammonium Chloride	190 g/l
MAZ Brightener 8480 ^a	50 ml/l
MAZ Brightener 8482 ^a	17.3 ml/l
pH	5.0-5.8
Temperature	30-35°C

^aProduct of Mac Dermid, Inc., Waterbury, Conn.

TABLE A-IV
CHROMATE SOLUTION

MACRO DRAB 6A ^a	1 PART (VOL)
MACRO DRAB 6B ^a	1 PART (VOL)
Water	10 PARTS (VOL)
Temperature	25°C
Time	30 TO 45 SECONDS

^aProduct of Mac Dermid, Inc., Waterbury, Conn.

**APPENDIX B--SAMPLE COMPUTATIONS OF THE FACTOR EFFECT
FOR A 2⁴ FACTORIAL DESIGN**

1. Write the average response (measured dependent variable) for each run to the right of the table (as in column heading $\bar{Y}$, Table B-I).
2. Total the values of the response on the lines with a plus sign for each column. Write the total on the line called Sum +. Do for all columns.
3. Do the same for the responses on the lines with minus signs. Write the total on the line called Sum -.
4. For each column subtract Sum - from Sum +. Write the result on the line called Difference.
5. For each column divide the Difference by the number of plus signs in that column (eight for this work). This number is the "effect" for that column.
6. Compute the variance (s^2) for each trial (see Reference 16 for methods of calculation).
7. Compute the standard deviation⁵ by adding up the sum of the variances for each trial and dividing the total by the number of degrees-of-freedom, which is equal to the number of tests at each condition minus one (i.e., $df = n - 1$).
8. Determine the minimum significant factor effect [MIN] from the formula $[MIN] = st \sqrt{2/mk}$ where
 - s = standard deviation
 - t = 2.09 at a 95% confidence level for 19 degrees-of-freedom
 - m = the number of + signs in the column
 - k = the number of tests at each condition
9. When a computed factor effect is larger than the minimum significant factor effect, then the experimenter can safely conclude that the factor is significant and will affect the results. Complete details are found in Reference 7.

The results of this calculation show that all test variables (strain rate, temperature, and environment) except surface condition (bare, plated) influenced the ultimate tensile strength of the U-Ti alloy. The interactions between the various variables (columns marked X_1X_3 , X_2X_3 , $X_1X_2X_3$, ...) were disregarded in this analysis.

Tables B-I through B-IV show the factor effects for the various tests.

TABLE B-1

EFFECT OF TEST ENVIRONMENT ON ULTIMATE TENSILE STRENGTH

Trial #	Mean	Strain rate 10 ⁻² / 1.0	Temperature -34°C/ 22°C	Environment Vac/ 100% H		Surface Condition Sare/ Plated										Average Ultimate Strength Tensile		s ²	df
		X ₁	X ₂	X ₁ X ₂	X ₃	X ₁ X ₃	X ₂ X ₃	X ₁ X ₂ X ₃	X ₄	X ₁ X ₄	X ₂ X ₄	X ₁ X ₂ X ₄	X ₃ X ₄	X ₁ X ₃ X ₄	X ₂ X ₃ X ₄	X ₁ X ₂ X ₃ X ₄			
1	+223	-	-	+	-	+	+	-	-	+	+	-	+	-	-	+	223	2.0	1
2	+234	+	-	-	-	-	+	+	-	-	+	+	+	+	-	-	234	37.0	1
3	+215	-	+	-	-	+	-	+	-	+	-	+	-	+	-	-	215	54.4	1
4	+221	+	+	+	-	-	-	-	-	-	-	+	+	+	+	+	221	0	0
5	+216	-	-	+	+	-	-	+	-	+	+	-	-	+	+	-	216	86.5	2
6	+231	+	-	-	+	+	-	-	-	-	+	+	-	-	+	+	231	3.13	1
7	+162	-	+	-	+	-	+	-	-	+	-	+	-	+	-	+	162	18	1
8	+222	+	+	+	+	+	+	+	-	-	-	-	-	-	-	-	222	2.3	1
9	+210	-	-	+	-	+	+	-	-	-	-	+	-	+	+	-	210	49	2
10	+225	+	-	-	-	-	+	+	+	+	-	-	-	-	+	+	225	.61	1
11	+214	-	+	-	-	+	-	+	+	-	+	-	-	+	-	+	214	2.5	2
12	+215	+	+	+	-	-	-	-	+	+	+	+	-	-	-	-	215	0	1
13	+236	-	-	+	+	-	-	+	+	-	-	+	-	-	-	+	236	242	1
14	+225	+	-	-	+	+	-	-	+	+	-	-	+	+	-	-	225	32	1
15	+203	-	+	-	+	-	+	-	+	-	+	-	-	-	+	-	203	16.5	2
16	+213	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	213	14.05	1
Sum +	3465	1786	1665	1756	1708	1753	1692	1775	1741	1694	1749	1716	1770	1695	1734	1725		745	19
Sum -	0	1679	1800	1712	1757	1712	1773	1690	1724	1771	1716	1749	1695	1770	1731	1740			
Check	3465	3465	3465	3465	3465	3465	3465	3465	3465	3465	3465	3465	3465	3465	3465	3465			
Diff	3465	107	-135	41	49	41	-81	85	17	-77	33	-33	75	3	-15	-15			
Effect	216.56	13.88	-16.88	5.88	-5.13	5.13	10.13	10.63	2.13	9.63	4.13	-4.13	9.38	-9.38	0.38	-1.88			37.5

s² = variance

s = standard deviation

t_{95,19} = 2.09

df = degrees of freedom

n = number of + signs in the column (8)

k = Number of replicates of each trial (2)

t = Probability points of t distribution

s² = 37.5

s = 6.12

[MIN] = st. $\sqrt{2/m}$

[MIN] = 4.36

TABLE B-II

INFLUENCE OF VARIOUS FACTOR EFFECTS ON THE MECHANICAL
PROPERTIES OF U-3/4 Ti STORED AT 70°C

	Yield Strength	Ultimate Tensile Strength	Elongation	RA
Strain Rate ($10^{-3}/1.0 \text{ sec}^{-1}$)	9.62 ^a	0.60	-2.53 ^b	-0.39
Storage Time (10/30 weeks)	13.10	2.38	-1.07	-0.45
Surface condition (Bare/Plated)	-1.04	-7.09	-1.35	-1.92
Environment (No HE/HE)	-1.10	1.17	0.76	1.12
[MIN] Minimum significant factor effect @95% confident level	2.79	2.63	2.72	4.00

^aBox values exceed the minimum significant factor effect.

^bStrain rate factor effect is sufficiently close to minimum significant factor effect that it probably influences elongation. However, for this report it is assumed that it has no effect.

TABLE B-III

INFLUENCE OF VARIOUS FACTOR EFFECTS ON THE MECHANICAL
PROPERTIES OF U-3/4 Ti AFTER 30 WEEKS STORAGE

	Yield Strength	Ultimate Tensile Strength	Elongation	RA
Strain Rate ($10^{-3}/1.0 \text{ sec}^{-1}$)	4.88	2.07	-2.17	1.04
Storage Temp. (50/70°C)	4.46	2.13	1.24	0.49
Surface condition (Bare/Plated)	-3.71	-8.17 ^a	0.82	-0.19
Environment (No HE/HE)	1.86	2.17	1.53	1.61
[MIN] Minimum significant factor effect @95% confident level	7.88	3.06	3.29	6.26

^aBox value exceeds the minimum significant factor effect.

TABLE B-IV
INFLUENCE OF VARIOUS FACTOR EFFECTS ON THE MECHANICAL
PROPERTIES OF U-3/4 Ti

	Yield Strength	Ultimate Tensile Strength	Elongation	RA
Strain Rate ($10^{-3}/1.0 \text{ sec}^{-1}$)	-	13.38	1.41 ^b	7.09
Temperature (-34/22°C)	-10.0 ^a	-16.88	5.69	12.84
Environment (Vacuum/100% RH)	5.0	-6.13	-3.79	-4.74
Surface condition (Bare/Plated)	1.00	2.13	0.91	1.06
[MIN] Minimum significant factor effect @95% confident level	3.99	4.03	1.51	1.01

^aBoxed value exceeds the minimum significant factor effect.

^bEnvironmental factor effect is sufficiently close to minimum significant factor effect that it probably influences yield strength. However, for this report it is assumed that it has no effect.

APPENDIX C--CALCULATION OF O_2 /U-Ti REACTION RATES

O_2 /U-Ti Reaction Rate Calculation

Calculation of O_2 Consumption

Empty container volume	277 cm ³
HE volume	36.9 cm ³
U-3/4 Ti specimen volume (two specimens)	8 cm ³
Total U-3/4 Ti surface area (two specimens)	49.5 cm ²
Initial O_2 volume % in air	21%
70°C bare specimens after 10 wk	19.0% with HE or 19.2% without HE
70°C bare specimens after 30 wk	13.2% with HE or 16.2% without HE

Reaction Rate Calculations, Using $PV = nRT$

Bare, no HE, 70 days

Pressure of oxygen	0.21 atm
Free volume	$277 - 8 = 269 \text{ cm}^3$
R (gas constant)	$= 82.057 \text{ cm}^3\text{-atm/K-mole}$
Temperature	300 K
Initial moles of O_2	$(21/100)(269)/(82.057)(300)$ $= 2.295 \times 10^{-3} \text{ moles}$
Fraction of O_2 used	$(21 - 19.2)/21 = 0.086$
Total moles O_2 consumed in 10 weeks	$(.086)(2.295 \times 10^{-3}) = 1.967 \times 10^{-4}$
Average reaction rate	$1.967 \times 10^{-4}/(70)(49.5)$ $= 5.67 \times 10^{-8} \text{ moles } O_2/\text{cm}^2\text{-day}$

Bare, with HE, 70 days

Free volume	232.1 cm^3
Initial moles of O_2	$(21/199)(232.1)/(82.057)(300)$ $= 1.980 \times 10^{-3} \text{ moles}$
Fraction of O_2 used	$(21 - 19)/21 = .0952 \text{ mole}$
Total moles O_2 consumed in 10 weeks	$(.0952)(1.980 \times 10^{-3})$ $= 1.836 \times 10^{-4} \text{ moles}$
Average reaction rate	$1.836 \times 10^{-4}/(70)(49.5)$ $= 5.44 \times 10^{-8} \text{ moles } \text{O}_2/\text{day-cm}^2$

Bare, no HE, 210 days

Free volume	269 cm^3
Initial O_2	$2.695 \times 10^{-3} \text{ moles}$
Fraction O_2 used	$(21 - 162)/21 = .229$
Total moles O_2 consumed in 30 weeks	$(.229)(2.295 \times 10^{-3})$ $= 5.29 \times 10^{-4} \text{ moles}$
Average reaction rate	$5.29 \times 10^{-4}/(210)(49.5)$ $= 5.05 \times 10^{-8} \text{ moles } \text{O}_2/\text{cm}^2\text{-day}$

Bare, HE, 210 days

Free volume	232.1 cm^2
Initial O_2	$1.98 \times 10^{-3} \text{ moles}$
Fraction O_2 used	$(21 - 13.2)/21 = 0.371$
Total moles O_2 consumed in 30 weeks	$(0.371)(1.98 \times 10^{-3}) = 7.35 \times 10^{-4} \text{ moles}$
Average reaction rate	$7.35 \times 10^{-4}/(210)(49.5)$ $= 7.07 \times 10^{-8} \text{ moles } \text{O}_2/\text{cm}^2\text{-day}$

Wairick Tests (Reference 5)

Free volume of container	33 cm^3
Initial O_2	$(21/100)(33)/(82.057)(300)$ $= 2.815 \times 10^{-4} \text{ moles } \text{O}_2$

Bare, 1 month

Fraction O_2 used	$(21 - 13.43)/21 = .360$
U disk area	$2 \times \pi[(1-3/8 \times 2.54)^2 - (3/16 \times 2.54)^2]$ $= 75.21$ $\pi[(.25 \times 2.54) \times (2-3/4)(2.54) = 13.93$ $\pi[(.25 \times 2.54) \times (3/8 \times 2.54)] = 1.90$ $75.21 + 13.93 + 1.90 = 91.04 \text{ cm}^2$
Total O_2 used	$(.360)(2.815 \times 10^{-4}) = 1.015 \times 10^{-4} \text{ moles}$
Rate assuming entire U-Ti area is active	$1.015 \times 10^{-4}/(28)(91.04)$ $= 3.981 \times 10^{-8} \text{ moles } \text{O}_2/\text{cm}^2\text{-day}$

Bare, 3 months

Fraction O_2 used	$(21 - .19)/21 = .99$
Total O_2 used	$.99(2.815 \times 10^{-4}) = 2.79 \times 10^{-4}$
Rate assuming entire U-Ti area is active	$2.79 \times 10^{-4}/(84)(91.04)$ $= 3.647 \times 10^{-8} \text{ moles/cm}^2\text{-day}$

It is probably incorrect to assume that the entire area is available for O_2 consumption at the maximum rate since one face of the disk is coated with silastic which might be expected to act as a partial barrier to O_2 access to the U-Ti. If it is assumed that this surface does not contribute to the O_2 consumption, the calculated rates become:

$$1 \text{ month}--1.015 \times 10^{-4}/(28)(53.44) = 6.78 \times 10^{-8} \text{ moles } \text{O}_2/\text{cm}^2\text{-day}$$

$$3 \text{ months}--2.790 \times 10^{-4}/(84)(53.44) = 6.21 \times 10^{-8} \text{ moles } \text{O}_2/\text{cm}^2\text{-day}$$

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