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ELECTROCHEMICAL MEASUREMENTS ON IODIDE BAR TITANIUM AT ELEVATED TEMPERATURES

H. S. Gadiyar

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Electrochemical Measurements on Iodide Bar Titanium at Elevated Temperatures

H. S. Gadiyar

ABSTRACT

Electrochemical measurements on iodide bar titanium have been made in oxygenated 0.05M K_2SO_4 and H_2SO_4 solutions at 240° and 257°C to obtain i-v characteristics, anodic film growth at constant potential, and in situ capacitance by pulse technique. Also included are AC impedance measurements made on these films at 25°C in different electrolytes. The work was done by G. H. Jenks, A. L. Bacarella, H. S. Gadiyar and A. L. Sutton. The purpose of this report is to record the data obtained. Interpretations are incomplete and will be included in other reports.

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Introduction:

In neutral and dilute acid solutions, titanium is normally passive and anodic polarization produces interference colored oxide films. Anodic oxide films on titanium between 25° and 90°C have been studied by others in the past.¹⁻⁵ Our data obtained on anodic film growth on iodide bar Ti (purity greater than 99.9%) in oxygenated 0.05M K_2SO_4 and 0.05M H_2SO_4 solutions at elevated temperatures are summarized in this report. The measurements included (1) current-voltage characteristics, (2) rate of film growth at constant anodic potential (0.00V* for 0.05M K_2SO_4 and + 0.3V for 0.05M H_2SO_4 solution), (3) in situ capacitance by pulse technique as a function of film thickness, and (4) activation energy determination between 200° and 240°C. Also included are room temperature AC impedance measurements for these films in different electrolytes. The work was done by G. H. Jenks, A. L. Bacarella, H. S. Gadiyar and A. L. Sutton. The purpose of this report is to record the data obtained. Interpretations are incomplete and will be included in other reports.

Experimental and Results:

Specimen preparation: Cylindrical specimens 2.25" long, 0.120" (dia.) were used. They were first polished mechanically up to 600 grit emery paper and then chemically polished in a freshly prepared solution containing 2:2:1 vol of lactic, nitric and HF (48%) acids. They were then washed thoroughly with distilled water before being introduced into the cell.

*The potentials were measured against Pt/ O_2 at constant temperature 55°C in the same solution.

Figures 1A and B: - The current-voltage characteristics of titanium obtained potentiostatically in $0.05\text{M K}_2\text{SO}_4 + 250 \text{ psig O}_2^*$ at 240°C are plotted. A small passive region between -0.1V to $+0.15\text{V}$ was observed. The film was grown at 0.00V where oxygen evolution was negligible. Values in the range of 1.0 to 1.7 were observed for $\alpha_c z_c$.

Figure 2: - Similar current-voltage characteristics in $0.05\text{M H}_2\text{SO}_4 + 250 \text{ psig O}_2$ at 240°C are shown. A passive region between $+0.1\text{V}$ to $+0.4\text{V}$ is shown in these plots. The film was grown at $+0.3\text{V}$. The $\alpha_c z_c$ values varied between 0.8 to 1.1.

Figure 3: - Corrosion rate (or film growth rate) is plotted as a function of time for two temperatures 240 and 257°C on a log-log scale. The film was grown in $0.05\text{M K}_2\text{SO}_4 + 250 \text{ psig O}_2$ at constant anodic potential of 0.00V . The rates went continuously from $5.5 \times 10^{-5} \text{ amp/cm}^2$ at the beginning of the experiment to very low values of $2.75 \times 10^{-8} \text{ amp/cm}^2$ after 8,500 min at 257°C and $4.2 \times 10^{-5} \text{ amp/cm}^2$ to $1.8 \times 10^{-8} \text{ amp/cm}^2$ after 8,500 min at 240°C . The slopes of these lines were between -0.92 and 0.98 ; approximately logarithmic kinetics of film growth. The total integrated thickness of the film after 8,500 min was about $280 \text{ \AA}$ at 240°C and $370 \text{ \AA}$ at 257°C . The thickness obtained from the interference color after the experiment was compared to the total integrated thickness. The agreement was good. This comparison was with colors obtained from experimental voltage-thickness color charts on the assumption of 24 to 25 $\text{\AA}$ volt (Appendix I).

*This oxygen pressure was at room temperature before heating up the cell.

Figure 4: - Represents corrosion rate-time curve at 240°C for films grown in 0.05M H_2SO_4 + 250 psig O_2 . The film was grown at 0.3V. The corrosion rate levelled off at 6.6 to 6.2×10^{-6} amp after an initial steady decrease up to about 400 min. After 1,000 minutes the rates went up a little and then decreased with further increasing time. A mixture of interference colors were observed on the specimen at the end of the run.

Figure 5: - Reciprocal rate vs time at two different temperatures 240° and 257°C are plotted for films grown in 0.05M K_2SO_4 solution. The straight lines are in conformance with logarithmic rate law. Deviations from the straight line occurred after long exposures at 257°C.

Figures 6a and b: - The reciprocal capacitance per unit area as a function of film thickness is presented for films grown in 0.05M K_2SO_4 solution. A linear relationship was observed. The dielectric constant obtained from these correspond to 411 to 415 at 240°C and 451 to 453 at 257°C.

Figure 7: - The dielectric constants obtained from capacitance measurements as a function of temperature while cooling at the end of the experiment are presented. Values of dielectric constants ranging from 200 to 220 were obtained at 25°C for these films.

Figures 8a and b: - Activation energy plots at the end of the experiments; values of 30 to 32 kcal/mole were observed in 0.05M K_2SO_4 solutions, while lower values ranging from 16 to 18 kcal/mole were observed in 0.05M H_2SO_4 solutions.

Table 1: The capacitance values as a function of film thickness in 0.05M H_2SO_4 solutions are presented along with integrated thicknesses. The specimen had a mixture of interference colors on examining at the end

of the run. The data for reciprocal capacitance (which is a function of thickness) and film growth rate presented in Table 1 did not follow logarithmic, cubic, or hyperbolic sine-function kinetics. Also $1/C$ vs X_T (integrated) was not a straight line.

AC Impedance Measurements:

The AC impedance measurements were made on these two films: Film I, grown in $0.05M K_2SO_4 + 250$ psig O_2 at constant anodic potential $0.00V$; temperature $257^\circ C$; total thickness $\sim 370 \text{ \AA}$. Film II, grown in $0.05M H_2SO_4 + 250$ psig O_2 at constant anodic potential $+ 0.3V$ (vs Pt/O_2); temperature $240^\circ C$, total thickness ~ 700 to $1000 \text{ \AA}$.

The measurements were made in three electrolytes, $0.05M K_2SO_4$, $0.05M H_2SO_4$ and $0.1M H_2SO_4$ for film I, and in $0.05M$ and $0.1M H_2SO_4$ for film II. The specimen was placed in a glass cell and a gold tube was used as subsidiary electrode. The results are plotted in Figs. 9A, 9B, 10A, 10B and 11. Straight line relations between $1/C_s$ vs $\log_{10} f$, R_T vs $1/f$, and $\tan \delta/C_s$ vs f are observed. The data for the films are summarized in Tables (2), (3) and (4); also included in Table 4 are the data for Zr and Nb for comparison. The $\tan \delta$ values for the oxide film varied from 0.354 to 0.223 from $1K$ Hz to $10K$ Hz. The values went up when the concentration of the electrolyte was increased from $0.05M H_2SO_4$ to $0.1M$.

The straight line relationships for the AC impedance components which are shown in the graphs are typical of those expected for non-porous dielectrics. However, the marked changes in capacitances with changes in composition of the electrolytes used in AC measurement indicates strongly that the oxides reacted with the electrolytes. Possibly solute ions (H^+ , OH^- , K^+) migrated into an oxide and occupied lattice

Table 1. Iodide Bar Ti; Corroded in 0.05M H_2SO_4 + 250 psig O_2
at Constant Anodic Potential +0.3V

(Temp. = 240°C) (Area of Specimen A = 5.2 cm²)

Time (min)	Rate amp/cm ² x 10 ⁷	Capacitance, C (total) (μf)	A/C = cm ² /μf x 10 ⁻²	X _T (Integrated thickness) Å
120	13.65	125.0	4.17	154
1,400	7.73	107.5	4.83	380
2,800	7.08	106.5	4.88	732
4,200	5.69	95.3	5.45	980
7,440	4.23	57.5	9.05	1,428
10,080	3.85	57.5	9.05	1,722

[Final thickness from the appearance of interference color was 700 Å to 1000 Å].

sites and thus altered the dielectric constant and the apparent resistance of the oxide. Further work would be needed to verify the mechanism of the electrolyte effects.

APPENDIX I

Studies on the formation of anodic oxide films by anodizing in K_2SO_4 and H_2SO_4 solutions.

The specimens used were cylindrical in shape. Approximate size: 2.25" long, 0.108" dia. Exact dimensions were found before anodizing.

Specimens were prepared by chemical polishing in 2:2:1 (by vol) of nitric, lactic and HF acids; polishing time 1 min. The specimen was then thoroughly swabbed in tap and distilled water, dried in oven at 100°C, and weighed using an Ainsworth semi-microbalance.

Solutions of H_2SO_4 and K_2SO_4 were prepared in triple distilled water.

While anodizing, the current was kept low (below 20 mA in K_2SO_4 and 40 mA in H_2SO_4 solution). Higher current densities were observed in H_2SO_4 solutions, and oxygen evolution was significant. The color changes were reproducible up to 80 volts in K_2SO_4 and 40 volts in H_2SO_4 solutions. A mixture of colors were observed sometimes in H_2SO_4 at voltages higher than 40 volts. The color changes are given in Table (a). The weight gains at different voltages and thicknesses calculated from these assuming $1 \mu g \text{ } O_2 / cm^2 = 58.7 \text{ } \text{\AA}$ are tabulated in Tables (b and c).

Table (a).

Anodizing Solution 0.05M K_2SO_4 (1 $\mu g O_2/cm^2 = 58.7 \text{ \AA}$)			Anodizing Solution 0.05M H_2SO_4 (1 $\mu g O_2/cm^2 = 58.7 \text{ \AA}$)		
Voltage (V)	Color Observed	Approximate Current Reached (mA)	Voltage (V)	Color Observed	Approximate Current Reached (mA)
5	Pale yellow	1	5	Pale yellow	1
10	Bright yellow to purple	3	10	Yellow	5
15	Deep red purple	7	15	Red purple	10
20	Purple & blue	9	20	Purple & blue	10
25	Blue	9	25	Satin blue	10
30	Light blue	7	30	Blue	10
35	Light blue	5	35	Deep blue	
40	Very light blue	5	40	Light blue	10
45	Very light blue	7			
50	Blue & yellow	7	50	(Pink & blue)?	10
60	Yellow	7	60	(Very light blue turning yellow)?	12
70	Gold	7	70	Light gold?	15
80	Deep gold	7	80	Purple + gold?	20
90	Gold	8	90	Blue + purple + gold?	30
100	Pink + gold	10	100	Purple + gold?	35
110	Deep pink	10	110	Green + yellow?	40
120	-- do -- + light blue?	10	120	Green + yellow + purple?	40
130	Blue	15	130	Light purple?	40

Table b. Anodizing Solution 0.05 M K_2SO_4
 Iodide Bar Ti Specimen (Cylindrical in shape).
 $1 \mu g O_2/cm^2 = 58.7 \text{ \AA}$.

Anodizing voltage	Wt. gain/cm ² ($\mu g/cm^2$ of O_2)	Total Thickness Calculated (x_T) $\text{\AA}$	Thickness/volt $\text{\AA}/\text{volt}$
40 v	17.5	1025	25.6
50	18.85	1105	22.1
60	21.0	1234	20.6
70	23.2	1362	19.5
90	28.0	1645	18.25
100	29.0	1700	17.0

Table c. Anodizing Solution = 0.05 H_2SO_4
 Iodide Bar Ti (cylindrical shape)
 $1 \mu g O_2/cm^2 = 58.7 \text{ \AA} (TiO_2)$

Anodizing voltage	Wt. gain/cm ² ($\mu g/cm^2$ of O_2)	Total Thickness Calculated (x_T) $\text{\AA}$	Thickness/volt $\text{\AA}/\text{volt}$
30 v	13.7	804	26.8
50	20.15	1182	23.6
70	23.7	1390	19.9
90	25.47	1495	16.6
110	26.2	1540	14.0
130	29.6	<u>1735</u>	13.35

Table 2. Film I. Iodide Bar Ti Corroded in 0.05M K_2SO_4 — 250 psig O_2 at
Constant Anode potential 0.00V; Temperature of Corrosion 257°C, $X_T \sim 370 \text{ \AA}$

A. Impedance measured in glass cell, using 0.05 M K_2SO_4 electrolyte, gold
tube as subsidiary electrode, 25°C. Area exposed = 1.5 cm^2 (Amp. 100 mv).

Frequency (Hz)	C_s (μf)	D	$\tan \delta$	$1/C_s$ $\times 10^5$	$\frac{\tan \delta}{C_s}$ $\times 10^5$	$R_T = \frac{\tan \delta}{\omega C_s}$	$\frac{1}{f}$ $\times 10^{-3}$	$\tan \delta$ for film
200	3.85	2.41	0.48	2.6	1.25	99.5	5.0	
500	2.98	0.95	0.47	3.36	1.58	50.2	2.0	0.417
800	2.67	0.58	0.46	3.74	1.74	34.7	1.25	0.374
1K	2.53	0.46	0.46	3.95	1.82	28.9	1.00	0.354
2K	2.14	0.25	0.50	4.67	2.32	18.5	0.5	0.300
4K	1.84	0.15	0.61	5.44	3.31	13.2	0.25	0.258
8K	1.63	0.10	0.82	6.13	5.00	9.95	0.125	0.228
10K	1.59	0.093	0.93	6.29	5.85	9.32	0.100	0.223
12K	1.55	0.086	1.03	6.47	6.66	8.82	0.0834	0.216
16K	1.48	0.078	1.24	6.76	8.38	8.34	0.0625	0.207
20K	1.44	0.073	1.46	6.94	10.12	8.06	0.05	0.202

Film I

B. Impedance measured in glass cell, 0.05M H_2SO_4 electrolyte at 25°C
Area = 1.5 cm^2

				$\times 10^5$	$\times 10^4$	Amplitude = 100 mv		
200	2.30	2.39	0.48	1.08	5.16	41.1	5.0	0.465
500	7.20	0.94	0.47	1.39	6.54	20.8	2.0	0.36
1K	5.90	0.44	0.44	1.70	7.46	11.9	1.0	0.313
2K	5.20	0.24	0.48	1.92	9.14	7.27	0.5	0.250
4K	4.61	0.15	0.60	2.17	13.0	5.17	0.25	0.231
8K	4.24	0.104	0.83	2.36	19.65	3.91	0.125	0.212
10K	4.13	0.097	0.97	2.42	23.5	3.74	0.100	0.207
12K	4.09	0.092	1.11	2.45	27.0	3.58	0.0834	0.205
16K	3.98	0.088	1.41	2.51	35.4	3.52	0.0625	0.199
20K	3.95	0.086	1.72	2.53	43.5	3.47	0.05	0.198

Film I

C. Impedance measured in glass cell, 0.1M H_2SO_4 electrolyte at 25°C

				$\times 10^4$	$\times 10^4$		$\times 10^{-3}$	
200	13.5	2.8	0.56	7.4	4.15	33.0	5.0	0.675
500	10.5	1.08	0.54	9.52	5.14	16.35	2.0	0.525
1K	8.25	0.498	0.498	12.1	6.02	9.58	1.0	0.437
2K	6.80	0.255	0.510	14.7	7.50	5.97	0.5	0.340
4K	5.80	0.138	0.55	17.25	9.52	3.79	0.25	0.290
6K	5.35	0.102	0.61	18.7	11.45	2.99	0.1665	0.268
10K	4.85	0.078	0.78	20.6	16.1	2.56	0.100	0.243
12K	4.78	0.071	0.85	20.9	17.8	2.36	0.0834	0.239
16K	4.60	0.063	1.01	21.7	21.9	2.18	0.0625	0.230
20K	4.59	0.061	1.22	21.8	26.6	2.12	0.05	0.230

Table 3. Film II. Iodide Bar Ti Corroded in 0.05M H_2SO_4 + 250 psig O_2 at Constant anode potential + 0.3V; Temperature of Corrosion 240°C, X_T 700 to 1000 Å.

D. Impedance measured in glass cell, 0.05M H_2SO_4 electrolyte, 25°C
Area exposed 1.5 cm² (amplitude 100 mv)

Frequency (Hz)	C_s (μf)	D	$\tan \delta$	$1/C_s$ $\times 10^5$	$\frac{\tan \delta}{C_s}$ $\times 10^4$	$R_T = \frac{\tan \delta}{\omega C_s}$	$1/f$ $\times 10^{-3}$	$\tan \delta$ for film
200	5.62	2.51	0.502	1.78	8.94	71.2	5.0	0.562
500	4.40	0.93	0.465	2.27	10.55	33.6	2.0	0.440
1K	3.85	0.51	0.51	2.60	13.25	15.92	1.0	0.385
2K	3.09	0.278	0.556	3.24	18.0	7.96	0.5	0.309
4K	3.72	0.178	0.712	3.68	26.2	3.98	0.25	0.372
8K	2.42	0.130	1.04	4.13	43.0	1.99	0.125	0.242
10K	2.40	0.120	1.20	4.17	50.0	1.592	0.100	0.240
12K	2.25	0.110	1.32	4.44	58.6	1.325	0.0834	0.225
16K	2.20	0.102	1.632	4.54	74.2	0.995	0.0625	0.220
20K	2.15	0.096	1.82	4.66	84.8	0.796	0.05	0.215

E. Impedance measured in glass cell, 0.1M H_2SO_4 electrolyte, 25°C

	$\times 10^4$	$\times 10^3$						
200	64.5	2.38	0.476	1.55	7.38	5.88	5.0	0.645
500	53.0	1.84	0.92	1.89	17.4	5.54	2.0	0.53
1K	46.0	0.95	0.95	2.17	20.6	3.28	1.0	0.46
2K	39.5	0.70	1.40	2.53	35.4	2.82	0.5	0.395
4K	38.0	0.52	2.08	2.63	54.7	2.18	0.25	0.38
8K	31.5	0.42	3.36	3.18	107.0	2.13	0.125	0.315
10K	30.2	0.40	4.0	3.31	132.5	2.11	0.100	0.302
12K	28.5	0.363	4.36	3.51	153.0	2.03	0.0834	0.285
16K	27.0	0.34	5.44	3.70	201.0	2.00	0.0625	0.270
20K	25.5	0.316	6.32	3.92	248.0	1.98	0.05	0.255

Table 4

Metal and History of Oxide Film	Electrolyte used for AC Impedance	Approximate Thickness of Film ($\bar{x}_T$)	Area of Surface Measured	Observed Intercept (I) on $\tan \delta / C_s$ on a plot of $\tan \delta / C_s$ vs f curve	Calculated Intercept (I) from slope of $1/C_s$ vs $\log_{10} f$ curve, if 'm' is the slope, Intercept $I = \frac{m \times 1.56}{2.303}$	Slope of $1/C_s$ vs $\log_{10} f$ line = m $\text{cm}^2 \text{ f}^{-1}$	Slope of R_T vs $1/f$ line = m_1 $R_T = \frac{\tan \delta}{\omega C_s}$ ohms, cm^2 , cycles	Ratio m/m_1	Parallel Resistance calculated at 10 kC/s. $R_p = (1 + \frac{1}{\omega^2 C_s^2 R_s^2})$ $R_p = \frac{1}{\omega} + \frac{1}{\omega I C_s^2}$	Capacitance (C_s) (μf)		tan δ for Film $\frac{(I \times C_s)}{10 \text{ kC/s}}$	
		($\bar{A}$)	(cm^2)	$\times 10^5$						1 kC	10kC/s	1 kC	10 kC/s
Iodide Bar Titanium Film grown in 0.05M K_2SO_4 at constant anodic potential 0.00V (vs Pt O_2) at 257°C (Film I)	A												
	0.05M K_2SO_4	350	1.5	1.43	1.52×10^5	2.25×10^5	2.14×10^4	10.5	47.34	2.53	1.59	0.354	0.223
	B												
	0.05M H_2SO_4	370	1.5	0.53	0.54×10^5	0.8×10^5	0.909×10^4	8.8	18.6	5.9	4.13	0.313	0.207
Iodide Bar Titanium Film grown in 0.05M H_2SO_4 at constant anodic potential 0.3V (vs Pt O_2) at 240°C (Film II)	C												
	0.1M H_2SO_4	370	1.5	0.53	0.54×10^5	0.8×10^5	0.729×10^4	10.9	13.6	8.25	4.85	0.437	0.243
	D												
	0.05M H_2SO_4	1000	1.5	0.975	1.05×10^5	1.55×10^5	1.39×10^4	11.15	29.9	3.85	2.4	0.385	0.240
Crystal Bar Zirconium Film grown in 0.05M H_2SO_4 at 233°C at constant anodic potential 0.00V (vs Pt O_2)	E												
	0.1M H_2SO_4	1000	1.5	0.100	0.088×10^5	0.13×10^5	0.211×10^4	5.78	1.91	46.0	30.2	0.46	0.302
	F												
	0.05M H_2SO_4	1800	0.51	5.2	5.32×10^5	7.8×10^5	8.48×10^4	9.65	5.21	0.0806	0.0758	0.0419	0.0394
Niobium (purity greater than 99.9%); Film grown in 0.05M K_2SO_4 at 195°C at constant anodic potential + 0.1V (vs Pt O_2)	G												
	0.05M K_2SO_4	700	0.55	2.75	2.85×10^5	4.2×10^5	4.45×10^4	9.44	151.4	0.853	0.627	0.234	0.173

Table 4: Electrical Properties of oxides formed by oxidation on Ti, Zr and Nb.

Fig. 1A. Current-Voltage for Iodide Bar Titanium in 0.05M K_2SO_4 + 250 psig, O_2 ; temperature of measurement = 240°C (Potentiostatic Measurement)

ORNL DWG. 67-6274

Fig. 1B. Current-Voltage Curve for Iodide Bar Titanium in 0.05M K_2SO_4 + 250
psig O_2 . Temperature of Measurement = 240°C. (Potentiostatic Measurement)

ORNL DWG. 67-6275

Fig. 2. Current-Voltage curve for Iodide Bar T1 in 0.05M H_2SO_4 + 250 psig O_2 ; Temperature = 240°C.

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Fig. 3. Corrosion rate (r) vs time (t).

Iodide Bar Ti in 0.05M K_2SO_4 + 250 psig O_2 Film growth is at constant anodic potential 0.00V vs Pt O_2 .1. $\circ$ = Temp. = 240°C; 2. Δ = Temp. = 257°C

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Fig. 4. Corrosion rate (r) vs time (t). Iodide Bar Ti in 0.05M H_2SO_4 + 250 psig O_2 .
Film growth at constant anodic potential + 0.3V vs Pt/ O_2 . Temp. = 240°C

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Fig. 5. Plot of $1/\text{Rate}$ vs time; Iodide Bar Ti; corroded in $0.05M K_2SO_4$ at constant anodic potential $0.00V$ vs Pt/O_2 .

1. Temp. = $240^\circ C$

2. Temp. = $257^\circ C$

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Fig. 7. Dielectric constant vs temperature; total thickness considered 370 Å.
Iodide Bar Ti, film grown in 0.05M K_2SO_4 + 250 psig O_2 at constant anodic potential 0.00V vs Pt/ O_2 .

Fig. 8(a) Activation Energy Plot for Iodide Bar Ti corroded in 0.05M K_2SO_4 + 250 psig O_2 at 240°C at
 constant anodic potential 0.00V vs Pt/ O_2
 (Corrosion time = 8,400 min, $X_{Ti} \sim 281 \text{ \AA}$)

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Fig. 8(b) Activation Energy Plot for Iodide Bar Ti corroded in
 in 0.05M H_2SO_4 + 250 psig O_2 at constant anodic potential + 0.3V vs Pt/ O_2
 (Corrosion Time = 7,100 min)

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Fig. 9A. Film I. formed by corroding at 257°C in 0.05M K_2SO_4 + 250 psig O_2 at constant anodic potential 0.00V vs Pt/ O_2

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Fig. 9B Film I. Formed by corroding at 257°C in 0.05 M K_2SO_4 + 250 psig O_2 at constant anodic potential 0.00V vs Pt/ O_2

Fig. 10A. Film II formed by corroding at 240°C in 0.05M H_2SO_4 + 250 psig O_2 at constant anodic potential + 0.03V vs Pt/ O_2

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Fig. 10B. Film II Formed by corroding at 240°C in 0.05M H_2SO_4 + 250 psig O_2 at constant anodic potential + 0.03V vs Pt/ O_2
 D. Measured in 0.05M H_2SO_4 electrolyte; glass cell, gold tube (Area exposed = 1.5 cm²) 25°C

Fig. 11. R_T as a function of $1/f$ for TiO_2 .

ORNL DWG. 67-6289

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