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DISSOLUTION OF ALUMINUM OXIDE AS A REGULATING FACTOR
IN AQUEOUS ALUMINUM CORROSION

By

R. L. Dillon

Materials Development
Reactor and Fuels Research and Development Operation

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ABSTRACT

The solubility of aluminum corrosion product in contact with metallic aluminum in deionized water has been determined over the range 80 - 350 C. Evidence is presented to show that oxide dissolution results in the formation of a porous oxide on aluminum exposed in refreshed dynamic systems. Dynamic corrosion rate data have been analyzed on the basis of parabolic film growth and a linear oxide degradation process acting simultaneously on the system. The degradation process has been shown to be a function of refreshment rate.

DISSOLUTION OF ALUMINUM OXIDE AS A REGULATING FACTOR
IN AQUEOUS ALUMINUM CORROSION

The results of corrosion testing aluminum in high temperature water at high flow rates have proven highly non-reproducible from one testing apparatus to another. At similar flow rates, temperatures and nominal water quality, dynamic corrosion rates have been found to vary by as much as a factor of 10.^(1, 2) From considerations of the aluminum corrosion process in static and dynamic systems, dissolution of the protective aluminum oxide corrosion product appears to be a likely factor in regulating dynamic aluminum corrosion.

Limiting the discussion to ~~resistant alloys~~⁶ such as X-8001, the corrosion of aluminum in static high temperature water proceeds by a parabolic rate process.⁽³⁾ There is a steady reduction in corrosion rate as the corrosion product film increases in thickness; in fact, the rate of the oxidation process is inversely proportional to film thickness. In contrast, the corrosion of aluminum in high temperature flowing water is linear with time and invariably more rapid, although as has been noted the actual rates are highly dependent on the test apparatus.

By inference, any process which reduces the corrosion product thickness, or increases the oxide porosity should increase the corrosion rate. In dynamic systems, either erosion or oxide dissolution could reduce the oxide thickness. The great variation in corrosion rates for systems operating at the same flow rate and temperature, suggests that some effect other than erosion, probably oxide solubility, is the major factor in aluminum corrosion. The effect of operating characteristics, particularly sample area and water refreshment rate, were found qualitatively in agreement with a solubility regulated process.

The objective of the studies reported here is an evaluation of oxide dissolution as the corrosion governing principle. To this end the solubility of aluminum corrosion product formed in the presence of metallic aluminum, has been determined as a function of temperature in deionized water. From the solubility data, corrosion rates have been estimated and compared with experiment.

EXPERIMENTAL

Direct analytical determination of dissolved corrosion product in solutions at high temperature and pressure is complicated primarily by the problem of transferring samples without alteration. For example, precipitation of aluminum oxide on the walls of the transfer vessel as the solution cools might introduce a serious sampling error. The accuracy of the analytical procedures available for small samples at aluminum concentrations of about 0.1 ppm is also questionable. The prospects for reliable solubility determination were generally better by the material balance method selected.

The experimental procedure is as follows: A weighted sample is placed in the autoclave, Figure 1. Water is pumped through the autoclave at a known rate and temperature. Equilibrium is maintained between water and corrosion product of sample by vigorous stirring. At the termination of the run, the sample is dried and weighed. The oxide is isolated from the metal by a methanol-iodine solution,^(4, 5) and dried two hours at 1200 C to convert it to anhydrous alumina. The aluminum lost to the system is calculated from the difference in weight of the unexposed sample and the sum of the post exposure weights of aluminum in the unreacted metal, in the adherent oxide, and the detached oxide filtered from the water. If the effluent water can be shown to be saturated with aluminum (calculated as Al_2O_3) the oxide loss divided by the volume of water passed through the system represents the solubility at the test temperature.

The water used in this study was distilled, passed through a mixed bed deionizer and stored in a covered aluminum tank. The specific

FIGURE 1

Sample Arrangement in the Stirred Autoclave

resistivity of the water was about 1.4 megohms, pH 5.7 to 5.9. Runs with off-standard water indicated corrosion product solubility is sensitive to water quality.

The mechanics of data collection and treatment are shown on a sample data sheet, Figure 2. The data collected are for sample CQ1751 (X-8001) and are representative of the data from which the report was prepared. A few of the entries require explanation:

Weight of Oxide Lost in Cutting. In order to reduce the time required to dissolve the untreated Al with the methanol-iodine solution, the sample was cut into small pieces to expose aluminum metal. The oxide lost in cutting is the difference in weight before and after cutting.

Per Cent Water (Baked at 1200 C). Weight loss versus time curves for corrosion product samples showed that baking for two hours at 1200 C brought the samples to constant weight.

Weight Oxide Dissolved. This figure is arrived at by the difference in weight of the total oxide formed and the amount recovered, both calculated as Al_2O_3 . Note that both oxide adhering to the sample and particulate oxide suspended in the solution are recovered.

Concentration of Dissolved Al Corrosion Product in the Effluent.

This quantity is the weight of oxide dissolved divided by the volume of water in liters passed through the autoclave in the course of the test.

Penetrations.

$$\frac{\text{Metal Loss (grams x 1000)}}{\text{Density of Al x area sample in inches}^2 \times 2.54^3} = \text{mils penetration}$$

Saturation of the System and Refreshment Rate

The validity of the material balance method for determining the solubility depends on the establishment of an equilibrium between solid and dissolved aluminum corrosion product. In the following discussion, procedures for determining solubility are described.

FIGURE 2DATA SHEET FOR SOLUBILITY EXPERIMENTS

Sample Number CQ1751	Dimensions of Sample 2" x 1/2" x 1/16
Temperature	250 C
Flow Rate	5.0 lph
Stirring Speed	780 rpm
Exposure Time	151 hours
Weight Sample Before Exposure	2.6936 grams
Weight Sample After Exposure and Cutting	2.6774 grams
Weight Oxide Isolated by $\text{CH}_3\text{OH}-\text{I}_2$ Dried at 120 C	0.0811 grams
Weight Oxide Lost in Cutting	0.0056 grams
Weight Oxide Filtered from Water Dried at 120 C	0.0277 grams
Total Weight Undissolved Oxide	0.1144 grams
Per Cent Water (Baked at 1200 C)	18.4%
Weight Recovered Oxide as Al_2O_3 $0.816 \times 0.1144 = 0.0934$ grams	0.0934 grams
Metal Lost	0.0973 grams
Weight Oxide Computed from Metal Lost $0.0973 \times \frac{102}{54} = 0.1838$ grams	0.1838 grams
Weight Oxide Dissolved	0.0904 grams
Concentration of Dissolved Al Corrosion Product in the Effluent	1.2×10^{-4} grams $\text{Al}_2\text{O}_3/\text{l}$
Penetration $\frac{0.0973 \times 1000}{2.7 \times 2.3 \times (2.54)^3} = 0.96$ mils	0.96 mils

In Figure 3 the calculated concentration of aluminum oxide in effluent 80 C, 300 Area tap water is shown graphically as a function of refreshment rate. The aluminum oxide concentration was found to remain constant up to a limiting refreshment rate. After the refreshment rate exceeded 0.73 L/hr, the concentration of corrosion product in the effluent tap water decreased as the refreshment rate was increased. Apparently the corrosion product concentration in the high refreshment range is controlled by a limiting rate at which oxide can be removed from the sample surface. The limiting dissolution rate is indicated by the fact that the product of effluent concentration and refreshment rate (i. e., the total oxide removed in unit time) remains constant as refreshment rate is increased.

Clearly the concentration plateau at low refreshment rate represents a solubility. At higher refreshment rates there is a transition from solubility to dissolution rate control of the corrosion product concentration.

In Figure 4 the concentration of the effluent water from the stirred autoclave operating at 300 C with deionized water is plotted as a function of refreshment rate. Again solubility and dissolution rate control regions are evident. In general, the demarcation between solubility and dissolution rate control is less well defined for deionized water than in the tap water example. This is partly due to the greatly reduced solubilities in deionized water and consequently greater scatter in concentrations.

In the region of dissolution rate control of concentration for deionized water systems, the product of concentration and refreshment rate tends to increase rather than remain constant as refreshment rate increases. A possible explanation for this behavior will be discussed in connection with the model for dynamic aluminum corrosion to be presented.

The Solubility of Aluminum Corrosion Product

In Figure 5, values for the corrosion product solubilities have been plotted as logs against the reciprocal of temperature. The data has been

FIGURE 3

Effluent Concentration of Al₂O₃ from 300 Area Tap
Water at 80°C

FIGURE 4

Effluent Concentration of Aluminum Corrosion Product
in Deionized Water at 300°C

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FIGURE 5

The Solubility of Aluminum Corrosion Product as a Function of Reciprocal Temperature. Heat of Solution at Infinite Dilution, ΔH_s , Calculated from the Slope Equals 2.3 Kcal.

extrapolated to lower temperatures for comparison with a literature value at 25 C from Alcoa's Aluminum Research Laboratories⁽⁶⁾ and an estimated value from Argonne.⁽⁷⁾

The solubilities plotted in Figure 5 are those of aluminum corrosion product formed in the presence of metallic aluminum at the indicated temperature. Aluminum corrosion product, however, is a complex material. X-ray analysis at Alcoa Aluminum Research Laboratory⁽⁸⁾, Bettis⁽⁹⁾ and the General Electric Research Laboratories⁽¹⁰⁾ have shown a variety of oxides and hydrates of aluminum to be present. The corrosion product tends to be largely hydrated at the surface and essentially anhydrous at the oxide-metal interface. The oxide or hydrate found at any point within the corrosion product depends on the temperature, length of exposure, distance from the oxide water interface, alloy composition and, perhaps, other variables.

It is a fair assumption that an observed solubility is associated with some one chemical species present in the corrosion product. This study has not attempted to establish what this chemical species might be. However, Deltombe and Pourbaix in their discussion of the aluminum-water system at 25 C have calculated solubilities in pure water for various aluminum oxides and hydrates from thermodynamic and electrochemical considerations.⁽¹¹⁾ In Figure 6 the solubility-pH curves for various hydrated aluminum oxides calculated by Deltombe and Pourbaix are shown. In this context the observed 25 C solubility for aluminum oxide formed on corroding aluminum is more similar to that calculated for corundum than any of the hydrates. By electron diffraction studies Hart⁽¹²⁾ has shown the corrosion product formed on 99.995 per cent aluminum at 20 C in high purity water consists of three layers. At the metal surface there is an amorphous oxide which hydrates to boehmite then to bayerite. One might speculate that anhydrous portions of the oxide would more nearly resemble corundum in stability (and solubility characteristics) than the

INFLUENCE OF pH ON THE SOLUBILITY OF Al_2O_3 AND ITS HYDRATES AT 25°C

Figure by Deltombe and Pourbaix (11)

FIGURE 6

hydrated species. This would lead one to the conclusion that the observed solubility is due to an anhydrous species being selectively leached out of the corrosion product.

The significance to be attached to the linearity of Figure 5 is not entirely clear. Linearity suggests that only one chemical species is involved in the dissolution process over the entire temperature range investigated. However, the uncertainties in the solubilities evaluated at the various temperatures make it difficult to detect small changes in slope. The ambiguity arises principally because we are dealing with a very small temperature dependence.

The temperature dependence found from Figure 4 corresponds to a value of 2.3 Kcal for the heat of solution at infinite dilution. The small endothermic heat of solution for so insoluble a compound indicates that associated with the dissolution process there is a large negative change in entropy. A somewhat similar situation occurs in the solution of silica in high temperature water.⁽¹³⁾ In both cases the dissolved oxide presumably orders a large amount of water in its hydration sphere.

Water Refreshment and Corrosion Rates

With an experimentally established corrosion product solubility versus water temperature curve, it is possible to inquire into the way corrosion is related to oxide dissolution. In Figure 7, average penetrations at 250 C for the rotated aluminum samples are plotted against the corrosion attributable directly to dissolution. The calculated loss from dissolution is the product of the effluent concentration of aluminum and the volume of water passed through the vessel in the course of the tests at 250 C. The significance of Figure 7 lies in the qualitative confirmation that as the volume of water contacting the sample increases so does corrosion. Allowing for the inevitable scatter of the data a more or less linear relation between corrosion and refreshment is suggested.

FIGURE 7

Relationship Between Observed Corrosion Penetration and Penetration Attributable to Corrosion Product Dissolution in 250°C Deionized Water

Corrosion losses in the stirred autoclave are approximately linear with water flow and relatively large with respect to those noted for the same exposure and temperature in static autoclaves. This suggests that the corrosion process consists of a parabolic film formation process plus an attack by water on the protective film which is linear with time. In an unpublished analysis of parabolic film formation and linear wash away, C. Groot has developed a treatment which, with certain mathematical adaptations, is applicable to corrosion in the stirred autoclave. ⁽¹⁴⁾

In developing the treatment the following symbols will be used:

A = thickness of Al sample in mils at any time

A_0 = thickness of Al sample in mils at time 0

F = equivalent thickness of aluminum in the protective corrosion product

W = equivalent thickness of aluminum in the nonprotective oxide and in the dissolved or detached corrosion product

τ = time in years

k_p = the experimentally determined parabolic rate constant

k_L = the linear rate constant for the degradation of the protective corrosion product

ϕ = penetration of the metal in mils (0.001 inch)

Assuming the sample has two corroding surfaces:

$$\frac{A_0 - A}{2} = \phi = F + W$$

$$\frac{d\phi}{dt} = \frac{k_p}{2F} = \frac{k_p}{2(\phi - W)} = - \frac{dA}{dt}$$

However, the rate of the degradation process, $\frac{dW}{dt}$, is constant with time so that:

$$W = k_L t$$

we can now write:

$$\frac{d\phi}{dt} = \frac{k_p}{2(\phi - k_L t)} = - \frac{dA}{dt}$$

inverting:

$$\frac{dt}{d\phi} = \frac{2\phi}{k_p} - \frac{2k_L t}{k_p}$$

$$\frac{dt}{d\phi} + \frac{2k_L t}{k_p} = \frac{2\phi}{k_p}$$

which is a linear differential equation of the first order which can be integrated by introducing a factor, $\exp\left(\frac{2\phi k_L}{k_p}\right)$

$$\exp\left(\frac{2\phi k_L}{k_p}\right) \frac{dt}{d\phi} + \frac{2k_L t}{k_p} \exp\left(\frac{2\phi k_L}{k_p}\right) = \frac{2\phi}{k_p} \exp\left(\frac{2\phi k_L}{k_p}\right)$$

$$\exp\left(\frac{2\phi k_L}{k_p}\right) t = \frac{2k_p}{4k_L^2} \exp\left(\frac{2\phi k_L}{k_p}\right) \left(\frac{2k_L}{k_p} \phi - 1\right) + C$$

$$t = \frac{k_p}{2k_L^2} \left(\frac{2k_L}{k_p} \phi - 1\right) + C \exp\left(\frac{-2\phi k_L}{k_p}\right)$$

$$= \frac{\phi}{k_L} - \frac{k_p}{2k_L^2} + C \exp\left(\frac{-2\phi k_L}{k_p}\right)$$

at $t = 0$, $\phi = 0$

therefore,

$$t = \frac{\phi}{k_L} - \frac{k_p}{2k_L^2} + \frac{k_p}{2k_L^2} \exp\left(\frac{-2\phi k_L}{k_p}\right)$$

$$t = \frac{k_p}{k_L^2} \left[\frac{\phi k_L}{k_p} + \frac{\exp\left(\frac{-2\phi k_L}{k_p}\right)}{2} - \frac{1}{2} \right] \quad (2)$$

Where $\frac{2\phi k_L}{k_p}$ has a value of 3.64 or more, the exponential term amounts to 1 per cent or less of the bracketed term and can, therefore, be neglected to simplify the calculation of k_L .

When $\frac{2\phi k_L}{k_p}$ is greater than 3.65,

$$t = \frac{k_p}{k_L^2} + \frac{\exp\left(\frac{-2\phi k_L}{k_p}\right) - \frac{1}{2}}{\frac{k_p}{k_L^2}} \approx \frac{\phi}{k_L} - \frac{k_p}{2k_L^2} \quad (3)$$

and

$$k_L = \frac{\phi + \sqrt{\phi^2 - 2k_p t}}{2t} \quad (4)$$

In Table I the linear rate constants k_L have been computed by formula (4) at five temperatures and for a variety of water refreshment rates.* These data have been used to develop Figure 8 in which k_L is shown graphically as a function of refreshment rate and temperature of the water.

The range of refreshment rate investigated in the course of this study should be considered in the perspective of existing isothermal test loops and in-reactor test facilities. Compared with any of the ex-reactor test data with which the writer is acquainted, the stirred autoclave refreshment rates per unit aluminum area are higher by a factor of 10 to 100. On the other hand the refreshment rates are in the range of those encountered in in-reactor test loops.

In discussing corrosion occurring in a non-isothermal system such as an aluminum clad fuel element in-reactor, an effective refreshment rate exists as a consequence of the ΔT in the system. As cooling water flows past power producing fuel elements the temperature of the water

* Under the conditions of most of the stirred-autoclave tests the contribution to the total corrosion from the parabolic process was negligibly small. As a result the observed corrosion divided by the exposure time in years is also a good approximation.

TABLE I
SUMMARY OF CONCENTRATION DATA
AND LINEAR DEGRADATION CONSTANTS

Sample Area in. ²	ϕ mils	t hours	k_L mils ² /yr*	Refreshment Rate L/in. ² /hr	Effluent Conc. Al ₂ O ₃ ppb
<u>80 C</u>					
1.25	-	3400	-	0.055	54***
1.25	-	1440	-	0.12	17
1.25	-	2360	-	0.17	20
<u>150 C</u> $k_p = 0.063$ mils ² /yr					
4.2	0.09	167	4.4	0.065	110
2.3	0.10	112	7.5	0.27	110
4.2	0.23	233	10.0	0.5	64
2.3	0.31	164	18.0	2.6	35
<u>200 C</u> $k_p = 0.36$ mils ² /yr					
2.3	0.17	160	8.2	0.28	130
2.3	0.23	168	11.2	0.34	160
2.3	0.42	264	13.6	0.65	100
2.3	0.67	165	35.5	2.3	90
<u>250 C</u> $k_p = 1.44$ mils ² /yr					
2.3	0.22	167	7.5**	0	-
2.3	0.47	168	22.9	0.43	170
2.3	0.48	170	23.2	0.43	
2.3	0.46	178	21.0	0.48	
2.3	0.47	134	29.0	0.91	150
4.2	0.65	166	33.4	1.04	160
4.2	1.27	417	28.8	1.04	130
2.3	0.72	164	37.4	1.18	140

TABLE I (contd.)

Sample Area in. ²	ϕ mils	t hours	k_L mils ² /yr*	Refreshment Rate L/in. ² /hr	Effluent Conc. Al ₂ O ₃ ppb
2.3	0.67	167	34.0	1.38	120
2.3	0.89	167	45.9	1.78	-
2.3	0.77	115	58.0	2.16	120
2.3	0.96	151	55.0	2.17	
2.3	0.85	123	60.0	2.65	100
2.3	0.78	140	48.0	2.65	
2.3	0.87	136	55.2	3.61	100
<u>300 C</u> $k_p = 4.6$ mils ² /yr					
8.6	0.42	144	17.4	0.21	-
3.6	0.29	80	16.0	0.23	-
3.6	0.55	139	29.6	0.24	-
2.3	1.61	491	27.4	0.55	250
2.3	0.85	159	43.7	0.76	200
2.3	1.51	420	30.1	0.90	210
2.3	0.60	115	41.5	0.95	190
4.2	1.64	314	44.5	1.17	-
2.3	0.93	162	47.6	1.9	120
2.3	1.14	162	56.9	2.5	140
2.3	1.21	160	65.4	3.5	90
<u>350 C</u> $k_p = 12.3$ mils ² /yr					
2.3	0.95	162	43.8	0.72	290
2.3	0.95	164	43.1	0.76	240
2.3	0.97	125	60.9	2.44	-

* k_L calculated from equation (4), $k_L = \frac{\phi + \sqrt{\phi^2 - 2k_p t}}{2t}$

** k_L approximated by equation (2)

*** Only a lower limit has been established for the effluent concentration of Al₂O₃ at 80 C (54 ppb). This is so indicated in Figure 5.

FIGURE 8

Corrosion Rates for Aluminum in the Stirred Autoclave
Rate Constant, k_L , Plotted as a Function of
Refreshment Rate and Temperature

increases, which in turn increases the capacity of the cooling water to dissolve corrosion product. It is this increase in oxide dissolving capacity associated with temperature rise, which can be likened to refreshment. During one in-reactor experiment, a ΔT of 9.5 C was calculated to occur in the coolant from one end of a fuel element of 44 in.² surface to the other. For this test the flow of water was 12 gpm at about 15 fps. The local corrosion product solubilities corresponding to the two ends of the piece at 240 and 250 C respectively were 1.86 and 1.95×10^{-4} g Al_2O_3 /liter. The increased capacity of the cooling water for aluminum oxide resulting from its increase in temperature can be likened to refreshment, in this case $\frac{0.09}{1.95} \times \frac{12 \times 3.78 \times 60}{44} = 2.9 \text{ L/hr/in.}^2$ for the refreshment rate. Referring this refreshment to the 250 C curve in Figure 8, a corrosion rate of about 53 mils a year should be expected. The observed rate in question was 70 mils a year.

A similar analysis has been made for tests of aluminum clad fuel elements in a different in-reactor test facility. In this case the flow was 60 gpm and the estimated local water temperature at the two ends of the piece 247 C and 250 C. Calculating an effective refreshment rate from the change in solubility expected for the observed temperature increase, the flow and aluminum surface area we get:

$$\frac{0.025}{1.95} \times \frac{60 \times 60 \times 3.78}{44} = 4 \text{ L/in.}^2/\text{hr.}$$

The experimental curve of k_L versus refreshment rate at 250 C can be extrapolated to 4 L/in.²/hr in a way to give a useful prediction. The value for the corrosion rate extrapolated from Figure 8 was 55 mils/yr; the observed rate was 50 mils/yr.

Mechanism

In proposing a model for aluminum corrosion in refreshed dynamic⁴ deionized water systems one must account for:

1. The increase in dissolution rate as refreshment rate is increased.
2. Simultaneous increase in corrosion rate and thickness of adherent oxide with increasing refreshment rate.

It is proposed here that the bulk oxide on stirred autoclave samples is porous as a result of the leaching action of the refreshed flowing water. The control of the corrosion process in the stirred autoclave is not associated with the porous bulk film, but with the fraction of the bulk oxide which has not been degraded by the leaching action of water. The portion of the total aluminum corroded associated with the formation of a protective oxide is deducible from the expression for the parabolic corrosion of aluminum in static water:

$$\frac{d\phi}{dt} \approx \frac{k_p}{2\phi}$$

It is necessary to postulate that the greater part of the oxide is non-protective (porous) in order to reconcile the corrosion rates observed in the stirred autoclave with those in static systems. Actually there is direct experimental evidence for high porosity in the corrosion product from dynamic tests. This matter will be discussed in detail in a report to be issued⁽¹⁷⁾ on the corrosion of Al in dynamic loops. However, it was found in one instance that the porosity per unit area of corrosion product from a sample exposed to flow rates of 25 fps, exceeded by a factor of 10 or more the porosity observed on a sample exposed simultaneously in the same loop but at low flow.

* For reference, the static corrosion model is thought to involve a protective bulk film which regulates corrosion by controlling the rate at which an oxygen species can diffuse inward towards the metal-oxide interface. (15, 16)

The porosity of the oxide or rather the increase in porosity attributable to oxide dissolution in samples exposed to rapidly recirculating water implies a selective dissolution process. That is, dissolution does not take place exclusively or even principally at the apparent water-oxide interface, but at cracks and fissures within the oxide. This is not surprising in view of the heterogeneous nature of the corrosion product. The wide variation of solubility within the corrosion product which can be expected as a result of hydration or aging has already been discussed.

These same loop studies have also shown that quite substantial reductions in corrosion rates can be obtained by autoclaving samples prior to loop testing. In this way an aged (hydrated) oxide is presented to the water.

One of the peculiarities of the solubility study in deionized water was the manner in which the effluent concentration changed with refreshment rate. Unlike aluminum corrosion product dissolution in treated Yakima River water, the concentration-refreshment curve for deionized water does not show a sharp break, or demarcation between solubility and dissolution rate control. To describe the anomaly for dissolution in deionized water one could say that the corrosion product appeared to dissolve too fast at high refreshment rates. An explanation of what might produce this effect is offered. The high porosity means that the true surface area from which dissolution might take place is a function of film thickness. At equivalent time the corrosion product is thicker for high refreshment rates and more porous, resulting in a large surface from which dissolution can take place.

The shape of the concentration versus refreshment rate curve could also be accounted for if the dissolving species changed. This does not appear to be the case. For one thing, solubility determinations within experimental error were independent of duration of the test.

FUTURE WORK

In the proposed corrosion model it was convenient to cite unpublished dynamic corrosion studies. The author has felt free to do this since the studies referred to will be included in a forthcoming document.

The basic approach described here might be extended in several directions. Very obviously more information on aluminum corrosion product solubility in treated Columbia River water and its effect on film properties could be helpful. Again as a practical matter it is recognized that the serviceability of aluminum in high temperature deionized water is greatly extended by small additions of phosphoric acid. There are qualitative indications that the corrosion process in phosphoric-acid-inhibited water is similar to deionized water. Information on corrosion product solubility in this inhibited water would be of assistance in predicting corrosion rates.

SUMMARY

1. The solubility of aluminum corrosion product has been determined over the range 100 - 350 C and extrapolated to literature values at room temperature.
2. Dynamic corrosion rate data have been analyzed on the basis of a parabolic film growth process and a linear oxide degradation process acting simultaneously on the system. The degradation process has been shown to be a function of refreshment rate.
3. A family of curves describing the linear film degradation process as a function of refreshment rate at various temperatures has been compiled.
4. A method for estimating corrosion rates in deionized water in-reactor from the corrosion rate-refreshment curves is described. Observed in-reactor corrosion rates are compared with predicted values.

5. Evidence is presented that the corrosion product on aluminum in dynamic refreshed deionized water is porous. Equivalent thicknesses are much less protective than corrosion product on aluminum in static or low flow systems.

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