TEMPERATURE AND HUMIDITY EFFECTS ON THE CORROSION OF ALUMINUM-BASE REACTOR FUEL CLADDING MATERIALS DURING DRY STORAGE

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ABSTRACT

The effect of temperature and relative humidity on the high temperature (up to 200 °C) corrosion of aluminum cladding alloys was investigated for dry storage of spent nuclear fuels. A dependency on alloy type and temperature was determined for saturated water vapor conditions. Models were developed to allow prediction of cladding behavior of 1100, 5052, and 6061 aluminum alloys for up to 50+ years at 100% relative humidity. Calculations show that for a closed system, corrosion stops after all moisture and oxygen is used up during corrosion reactions with aluminum alloys.

I. INTRODUCTION

Many research and test reactors including Savannah River Reactors are operated using aluminum clad fuel elements with either aluminum-uranium or aluminum-uranium silicide cores. After irradiation, the spent fuel must be stored or reprocessed to maintain safe environmental conditions. Countries are considering dry storage as an option for temporary storage and several are already storing some of their spent fuel using this method. In the US, dry storage is being proposed for aluminum based fuels, but before a facility is built, a technical basis needs to be established to define the acceptance criteria for 50+ years of safe storage.

Degradation of the fuel due to corrosion of the aluminum is a major concern for dry storage where corrosive environments exist. Therefore, storage conditions must be specified for maximum cladding temperature, cover gas requirements, and drying procedures to avoid excessive degradation. Under ideal conditions, where all moisture and oxygen are excluded from a sealed storage container and the temperature is limited, aluminum fuels can be stored without oxidation. Achieving and maintaining ideal conditions would be economically prohibitive, therefore, limited degradation must be acceptable. Any spent fuel storage in today's regulatory environment will require validation and verification that acceptable conditions exist and can be maintained throughout the storage period. Also, the state of the fuel must be predicted from corrosion models in the event that the acceptable storage conditions can not be maintained for long times.

To evaluate the corrosion behavior of various aluminum alloys, studies are being carried out at Westinghouse Savannah River Company. [1-4] Tests were conducted at 150°C and 200°C in air at saturated water vapor conditions (100% relative humidity) for exposure times up to about 1400 hours. Gamma radiolysis produces NO_x gases when air is present, and if moisture is also present, nitric acid can be produced. These effects on the corrosion behavior of aluminum alloys were also evaluated for storage of spent reactor fuels.

II. ATMOSPHERIC CORROSION

Although aluminum is a very reactive metal, it generally has good corrosion resistance. In air, its stability is primarily due to a thin layer of amorphous aluminum oxide which forms rapidly on exposed aluminum surfaces. The molecular volume of the oxide is 1.5 times the volume of aluminum consumed which puts the oxide surface in compression and allows some deformation of the surface without rupturing the oxide film.[5] Water, present as vapor in the atmosphere, can cause continuous corrosion of aluminum especially at high humidities and temperatures.

General Corrosion

General or uniform corrosion is effected by the chemical composition of the corrosive medium or electrolyte. Water, one of the major components in the atmosphere, condenses on the surface of metals and serves as the electrochemical path for corrosion reactions. The water or moisture content in air can be expressed by its relative humidity (Rh) which is defined as the ratio of the water vapor pressure to the saturation vapor pressure at a given temperature. It is generally expressed as a percent.

Water from a humid environment can be deposited on the surface of a metal by condensation and absorption. The amount of moisture absorbed varies with the relative humidity and temperature. Volpe[6] determined that, at 20 °C in moderately humid atmospheres of about 30% Rh, more than 10 monolayers of water are present. At 100% relative humidity, the absorbed layer more than doubled. Investigators[7,8] have also found that there is a critical humidity between 40 and 70% below which practically no corrosion occurs at room temperature. The critical value for the relative humidity appears to depend on the electrolyte composition, the previous amount of corrosion and possibly temperature.

When aluminum is first exposed to the atmosphere, a thin continuous film of amorphous oxide quickly forms. On continued exposure, a layer of hydrated oxide grows and can have several different crystalline phases depending on the reaction temperature and the presence of water. For example, at temperatures less than about 80°C bayerite ($Al_2O_3.3H_2O$) forms while above 80 °C boehmite ($Al_2O_3.H_2O$) forms on the surface of aluminum. These hydrated oxides are reported to be highly porous compared to the layer of amorphous Al_2O_3.[9]

Water in the atmosphere contains both dissolved solids and gases, particularly in industrial areas. Aluminum compounds that have been found in the corrosion layers include oxides and hydrated variants of sulfates and chlorides. Nitrates have not been detected on surfaces of aluminum exposed to natural environments.[10] The reason, most likely, is because all nitrates are water soluble and would be leached from the surface by excess water. Also, Nguyen and Foley[11] found that the nitrate ion is reduced by aluminum but not aluminum oxide; thus, interaction with the aluminum substrate occurs when there is a defective oxide surface.

III. GAMMA RADIOLYSIS

In a radiation field, oxides of nitrogen are produced by gamma radiolysis of air. These compounds can further react with moisture to produce nitric acid. The concentration of species formed depends on (1) the nature of the ionizing radiation (2) the dose rate (3) the total dose and (4) impurities.

Primak and Fuchs[12] studied the behavior of metals exposed to ionizing radiation in humid air and reported that certain metals and alloys are subject to nitric acid corrosion when irradiated in moist air. Nitrogen and oxygen combined in the gas phase to coat nitric-acid susceptible metals with nitrates in the presence of water vapor. It was found that aluminum, cobalt, copper, inconel, lead, and nickel were coated with nitrates after irradiation. Additionally, Steinberg[13] reported results of in-pile capsule irradiation of nitrogen-oxygen gas mixtures. Relatively high concentrations of nitrogen oxides were built up. More than 90% of the oxygen in the mixture was converted to gaseous oxides of N_2O_4, NO_2 and N_2O at steady state conditions. Johansson[14] observed significant increased corrosion of aluminum when NO_2 was added to SO_2 in high humid atmospheres. The reaction of NO_2 with moisture can occur according to the following chemical equation:

$$2NO_2 + H_2O \text{ (moisture)} \dashrightarrow HNO_2 + H^+ + NO_3^- \qquad (1)$$

The HNO_2 produced by this reaction is unstable and is known only in solution.[15] In the presence of air, further nitric acid may be formed by oxidation of the HNO_2 acid. Evidence of increased corrosion due to radiolysis was discovered also at the Savannah River Site[16] where accelerated corrosion of steel occurred in the reactor process room.

Nitric acid, therefore, forms on the solid metal surface to influence corrosion behavior. In a closed system, however, reactions to produce nitric oxides stop once the moisture and oxygen in the air is depleted by oxidation reactions with metal surfaces.

IV. CORROSION MODELS

The basic corrosion process is well understood at high temperature. Ionic compounds have appreciable ionic conductivity due to Schottky and/or Frenkel defects. Metal cations diffuse interstitially or by diffusion to vacanies in the oxide lattice. Oxidation continues as metallic ions move through the film to the oxide/oxygen interface where they combine to form the metal oxide. The growth rate for general corrosion is related to the weight gain of the material and is proportional to the ion concentration gradient. From this relationship, the general power law follows:

$$W = (C\,t)^n \qquad (2)$$

where W is the oxide thickness or weight gain, C is a constant depending on ion concentration, t is the exposure time, and n is an exponent theoretically equal to 0.5 for parabolic growth. The constant C is related to the concentration of the diffusing species so that its effects may be modeled using the Arrhenius relationship.[17] The resulting equation becomes:

$$W = A\,e^{-Qn/RT}\,t^n \qquad (3)$$

where A is a constant dependent on the material and humidity, Q is the activation energy, R is the universal gas constant, and T is the absolute temperature. Tahboub et al.[18] investigated the oxidation of bismuth and its dilute alloys in air at temperatures between 500 and 530 K and found that the weight gained at a given temperature followed this type law. Other models have been used to describe low temperature oxidation such as the logarithmic and inverse logarithmic laws, but they will not be discussed in this paper.

V. MATERIALS CHARACTERIZATION

Research and test reactor fuel elements are clad with aluminum alloys that have been qualified for reactor service. A list of some of the cladding materials along with the maximum allowable alloying elements is given in Table I for foreign research reactor (FRR) fuels. Because these alloys were not available, corrosion tests, reported in this paper, were carried out using 1100, 5052 and 6061 aluminum alloys. Although the compositions of these alloys do not identically match the FRR materials, they are expected to exhibit similar corrosion behavior. Results from x-ray fluorescence analysis of aluminum alloys used in this investigation are given in Table II.

The 1100 aluminum alloy is a commercially pure material containing basically iron silicon and copper with other trace impurities. This material has been used as a cladding material for heavy water reactor target elements at the Savannah River Site. Alloy 5052 contains typically 2.5% magnesium and 0.25% chromium. This high magnesium alloy contains alloying elements similar to CERCA'S AG alloys and NUKEM'S AlMg alloys. Aluminum 6061 is a precipitation hardening alloy containing typically about 1% magnesium, 0.6% silicon and 0.3% chromium. This alloy is used as a cladding material for the HFIR fuel elements in the US and for cladding on other reactor fuel elements made by Babcock and Wilcox. Some FRR cladding alloys may have slightly higher copper and either higher or lower magnesium contents.

The aluminum coupons used in the corrosion tests were obtained from Metal Samples(*). They were machined from 1100-H14, 5052-H32 and 6061-T6 sheet

(*) *Metal Samples Co., Munford, Alabama, 36268.*

material and ground on a belt sander to give a 600 grit surface finish. The temper designations for aluminum alloys are:

H14 -	Strain hardened only (16-21 Ksi tensile)
H32 -	Strain hardened and stabilized by a low temperature thermal treatment
T6 -	Solution heat treated and artificially aged(46.5-46.6 Ksi tensile).

Optical photomicrographs of the three alloys in the as-received condition are shown in Figure 1. The etching solution to bring out the microstructure was a mixture of 90 ml of water and 10 ml of hydrofluoric acid. Elongated grains in the cold worked microstructure for the 1100 and 5052 alloys can be seen in (a) and (b) while equiaxed grains of the solution annealed and aged 6061 are evident in (c). Scanning electron microscopy and x-ray spectroscopy was used to identify the basic composition of the precipitates. Precipitate compositions consist of (1) aluminum-iron-copper in 1100, (2) aluminum-iron-chromium in 5052 and (3) aluminum-iron-copper-chromium in 6061.

VI. EXPERIMENTAL METHODS

Condensate Water

Condensate water was used so atmospheric impurities, characteristic to the Savannah River Site, could be included in the test matrix. The water from the atmosphere was obtained using a condensing coil and collected in a polyethylene bottle. Instrumental chemical analysis for elemental impurities was done using Inductive Coupled Plasma (ICP). Anion analysis was done by Ion Chromatography. The results for elements detected as significant are given in Table III along with pH and conductivity measurements.

Autoclave tests

Corrosion tests in the autoclave were carried out in a one-gallon, stainless steel vessel that was manufactured by Autoclave Engineers(*). Tests were done at 150 and 200°C using both condensed water and a solution of condensed water and nitric acid. The solution of 10 wt% concentrated nitric acid in condensed water, having a pH of approximately 1, was used to provide nitric oxide vapors inside the autoclave at 150°C. The oxide vapors simulated the build up of these gases by radiolysis in a dry storage container with air and moisture.

The aluminum test coupons were isolated from the stainless steel vessel wall to eliminate galvanic effects on corrosion behavior. A Teflon plate was bolted to the top of the vessel and aluminum hangers were attached to the plate with aluminum nuts to support the specimens. Shallow grooves in the hangers kept the specimens apart to minimize crevice corrosion. Up to 28 specimen could be tested during one cycle. All coupons were cleaned before beginning the test by using acetone to remove oils and then rinsed thoroughly in distilled water and alcohol before drying. No attempt was made to remove the oxide layer from the as-received aluminum coupons before corrosion testing.

(*) *Autoclave Engineers, Inc., Erie, Pennsylvania, 16512-5051*

The autoclave vessel was helium leak checked prior to corrosion testing. For corrosion tests, 150 cc of condensate water or acid-water solution was added to the vessel. This quantity of liquid exceeded the minimum requirements needed to maintain saturated water vapor conditions throughout the test. After the controller was turned on, it took about one hour to reach steady state temperature conditions.

The vessel pressure was measured using a Sensotec pressure transducer, model TJE/71a3-18(*) and a HM signal conditioner with RS-232 output for data acquisition. A chromel-alumel thermocouple inside the thermowell of the vessel measured the temperature in the vicinity of the test specimens. Temperature data were read and transmitted to the acquisition system using a Newport INFINITY temperature meter(**).

The relative humidity was measured using a Vaisala HMP-234 humidity and temperature instrument(***). The probe read data from inside the autoclave for temperatures up to 180 °C maximum. It has a pressure rating of 100 bars (1450 psi) and an accuracy of about +/- 2% at 90 to 100% Rh.

The software for data acquisition was written in Microsoft C language and recorded temperature, pressure and relative humidity as a function of time. Data were taken at 0.25 hour intervals. A typical pressure-temperature chart is shown in Figure 2.

Air inside the autoclave was at atmospheric pressure at the beginning of the test. As the autoclave temperature increased the air pressure and the water vapor pressure increased so that the total pressure inside the autoclave was the sum of both pressures. Air inside the vessel was vented to the atmosphere for approximately 15 seconds when the temperature reached 100 °C, thus, leaving mostly water vapor present during corrosion testing.

The relative humidity inside the autoclave was calculated from temperature and pressure data as a backup to measured humidity values. The saturation water vapor pressure for the calculation was determined as a function of temperature by fitting equations to thermodynamic steam data.[19] Calculated values for the relative humidity were necessary at temperatures above 180 °C which was the maximum operating temperature of the humidity probe and for acid-water solution tests. The derived relative humidity (%) equation is:

$$Rh = (1/P_s)(100P_t + K[T+273]) \quad (4)$$

where P_s is the saturation vapor pressure in pounds per square inch absolute (psia) at temperature T in degrees centigrade and P_t is the total measured pressure (psia) inside the autoclave. The total pressure includes the pressure due to both water vapor and air, if present. The value of the constant K is determined from room temperature conditions and represents air inside the autoclave before the top is bolted in place. The value of K is:

$$K = (Rh_r \times P_s - 1470)/(T_r + 273) \quad (5)$$

(*) *Sensotec, 1200 Chesapeake Ave., Columbus, Ohio.*

(**) *Newport Electronics, Inc., 2229 South Street, Sanata Ana, CA.*

(***) *Vaisala Inc., Woburn, MA 01801 - 1068.*

where Rh_r is the relative humidity of the room air in percent and P_s is the saturation vapor pressure at room temperature T_r in degrees centigrade. When the autoclave is vented to remove the air inside the vessel, the value of K is equal to zero.

Corrosion tests of aluminum alloys were conducted in the autoclave at 150 or 200 °C with a constant relative humidity of 100%. After specified time intervals, the autoclave was shut down and the samples removed. They were dried for about 30 minutes in a desiccator under a vacuum of about 10^{-2} torr. This was done to remove any liquid from the surface before weighing.

Sample Weighing

Each aluminum coupon was weighed three separate times on a 5 place microbalance and the weights averaged to obtain weight gain data for the aluminum coupons. Standards were weighed before each sample to verify balance accuracy.

VII. RESULTS

Condensed Water Tests:

Typical coupons from autoclave tests at 200 °C and 100% Rh (100% condensed water vapor) are shown in Figure 3 for 6061 aluminum. Corrosion was evident in the photographs by the disappearance of longitudinal scratches and dulling of the surface. X-ray diffraction of the oxide confirmed that boehmite formed at both 150 and 200 °C on all test samples.

Weight gain data (micrograms/dm^2) are plotted as a function of time at 100% Rh in Figures 4, 5, and 6 for 1100, 5052 and 6061 alloys, respectively. Power law equations with the Arrhenius term were fit to the data using numerical least squares analysis. In the figures, solid curves represent results for 200 °C and broken curves for 150 °C. Values for the constants and exponents are given in Table IV.

The thickness of the oxide layer after about 1400 hours ($^{\sim}$2 months) at 200 °C was measured from 500 X optical photomicrographs using a 5X magnifier containing a metric measuring scale. About 25 thickness readings were made randomly from five different photographs of selected specimens that were exposed to condensed water vapor for approximately 1400 hours. The readings were averaged to give arithmetic mean thicknesses of 6.1, 6.2 and 4.4 microns for 1100, 5052 and 6061, respectively. The calculated values for the oxide thicknesses were obtained from weight gain data and determined to be 6.0, 6.5 and 4.3 microns, respectively.

Using the experimental weight gain equations for the aluminum alloys, the change in water vapor and pressure inside a 70 ml vessel was determined as a function of time at 150 °C. It was assumed that only the moisture reacted with the aluminum according to equation (6) given below. It was assumed that one coupon each of 1100, 5052 and

6061 aluminum was inside the vessel. Corrosion of the aluminum alloys was assumed to take place according to the reaction:

$$2Al + 4H_2O \rightarrow Al_2O_3.H_2O + 3H_2(gas) \qquad (6)$$

The aluminum corroded according to the models developed in this study, and the gases were assumed to obey the perfect gas law and Dalton's law of partial pressure. The results of the calculations are shown in Figure 7. The water vapor decreased as a function of exposure time while the hydrogen pressure increased to about 3.9 kg/cm^2 (55 psi). After 5.6 years, all of the moisture is depleted from inside the vessel and corrosion due to the moisture stops. Oxygen in the air also contributes to corrosion, but its effect was not modeled in this calculation. At higher temperatures, the time required to deplete the water vapor would be less because of increased corrosion of aluminum.

Nitric Acid Water Test:

When corrosion experiments were carried out at 100% Rh and with nitric acid to simulate radiolysis, severe corrosion of all specimens took place as shown in Figure 8. In one week the samples had corroded so badly that it was difficult to remove them from the hangers. Aluminum oxide sluffed from the surfaces and was found in the bottom of the autoclave. X-ray diffraction confirmed that both the sluffed oxide and the oxide on the sample surfaces were boehmite. No evidence of nitric oxides or compounds were found in the aluminum oxide samples. A severely pitted surface was observed after the oxide was removed from the 5052 alloy sample. The observed maximum pit depth was 1 mm. The 1100 and 6061 aluminum alloys did not exhibit pitting corrosion.

VIII. DISCUSSION

CORROSION OF ALUMINUM

Autoclave results indicate that corrosion of aluminum alloys in saturated water vapor at 150 and 200 °C follows the power law relationship where temperature effects are modeled using the Arrhenius relationship, equation (3).

Curves were fit to the weight gain data. The correlation coefficients (R^2) for 1100, 5052 and 6061 were 0.93, 0.87 and 0.91, respectively. The exponents (n) in the equations were found to be 0.41, 0.55 and 0.45. These values are close to the theoretical value of 0.5 for high temperature parabolic corrosion. The activation energy (Q) was calculated to be 22, 20 and 16 kcal/mole for 1100, 5052 and 6061 aluminum alloys, respectively. The published value for the activation energy for aluminum from data in the temperature range of 40 to 100 °C is 18.7 kcal/mole.[5]

The metallurgical results from the present study at high temperatures and 100% Rh show that a uniform film of boehmite, characteristic of general corrosion, forms on all alloys at the test conditions in water vapor environments. Uniform growth in thickness is expected to continue until spallation occurs at film thicknesses of approximately 50 microns. It has been observed that sluffing takes place when the oxide thickness is greater than about 50 microns.[20] Under nitric oxide vapor conditions, sever corrosion took place and pitting occurred after 1 week exposue for the 5052 aluinum alloy.

Extrapolation of the data (converted to oxide thickness of boehmite) to 50 years using a log-log plot gives average film thicknesses of 19, 33 and 21 microns for 1100, 5052, and 6061 at 150 °C and 59, 134 and 52 microns for these alloys at 200 °C, respectively. The corresponding thickness of metal consumed, assuming no sluffing of the oxide, was determined to be 11, 19 and 12 microns at 150 °C and 33, 76 and 30 microns at 200 °C, respectively. Incremental calculations have not been done to take into account oxide sluffing.

At about 1400 hours and 200 °C, the group of data points for each alloy are just above the power law curves. This observation may indicate a change in film growth mechanisms or cracking of the oxide barrier. Further study is needed to investigate this behavior.

Calculations for a 70 ml closed vessel show that the water vapor inside the closed vessel decreases from its initial saturation condition as aluminum corrosion reactions take place. Hydrogen gas pressure increases inside the sealed system until corrosion reactions stop. The total pressure decreases about 19% over the saturation pressure and the water vapor pressure is zero after 5.6 years. Moisture inside the sealed vessel is used up and corrosion eventually stops. The amount of water vapor inside the sealed system depends on the initial relative humidity and will effect the time when corrosion reactions stop.

IX. CONCLUSION

Corrosion experiments were performed at 150 and 200 °C under 100% Rh conditions and up to 1400 hours for aluminum cladding materials. These conditions represent the worst case for storage of spent nuclear fuel. Results show a dependency on alloy type and temperature. Corrosion behavior was modeled using a power law containing an Arrhenius term. The equations allow for weight gain predictions for long-term (50+ years) storage of aluminum alloys as a function to time and temperature in a constant 100% Rh environment. Metal loss, if general corrosion continues according to the model and no sluffing of the oxide film occurs, is predicted to be about 33(1.3 mils), 76(3 mils), and 30(1.2 mils) microns for 1100, 5052 and 6061 aluminum alloys, respectively after 50 years.

Nitrogen oxides are formed by radiolysis and would greatly accelerate corrosion in a dry storage system where moisture is present. Calculations using experimental data show that the corrosion stops after aluminum reactions deplete all oxygen and moisture from inside a closed vessel. Tests are continuing at various initial humidity levels to investigate the corrosion kinetics of these conditions for long storage times in a sealed system.

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Table I

TYPICAL COMPOSITIONS OF CLADDING MATERIALS FOR FOREIGN RESEARCH REACTORS

Fuel Manufacturer*

	CERCA				NUKEM		B&W
Element	**AG1**	**AG2**	**AG3**	**AlFeNi**	**AlMg1**	**AlMg2**	**6061**
Mg	1.1-1.4	1.8-2.3	2.5-3.0	0.8-1.2	0.7-1.1	1.7-2.4	0.8-1.2
B	-	0.001	-	0.001	0.001	0.001	0.001
Cd	-	0.001	-	0.001	0.001	0.001	0.001
Cu	-	0.008	-	0.008	0.008	0.008	0.2-0.40
Fe	-	0.2-0.4	-	0.8-1.2	0.45	0.40	0.70
Si	-	0.3	-	0.30	0.30	0.30	0.40-0.80
Cr	-	0.3	-	0.2-0.5	0.10	0.30	0.04-0.35
Mn	-	0.7	-	0.2-0.6	0.15	0.30	0.15
Li	-	0.001	-	0.001	0.001	0.001	0.008
Zn	-	-	-	0.06-0.14	0.05	0.03	0.25
Ti	-	-	-	0.02-0.08	-	0.10	0.25
Al	-	Balance	-	Balance	Balance	Balance	Balance
Others	-	0.03	-	0.03	0.15	0.15	0.15

* Reference: IAEA Guide Book on Fuels, pp41-47.

Table II

X-RAY FLUORESCENCE ANALYSIS OF ALUMINUM ALLOY MATERIALS FOR CORROSION TESTING AND ALUMINUM COMPANY OF AMERICA COMPOSITION LIMITS

	Element Weight Percent												
Alloy	Si	Fe	Cu	Mn	Cr	Ni	Zn	Ti	V	Ga	Zr	Mg	Al
1100	0.104	0.521	0.128	0.005	0.007	0.009	0.009	0.007	0.008	0.011	0	0.012	99.17
1100 Limits	1.0		0.05 - 2.0	0.05	-	-	-	0.1	-	-	-	-	Bal.
5052	0.116	0.284	0.014	0.022	0.188	0.012	0.011	0.019	0.012	0.013	0.001	2.522	96.78
5052 Limits	0.45		1.0	0.10	0.15 - 0.35	-	-	-	-	-	0.10	2.2 - 2.8	Bal.
6061	0.613	0.497	0.30	0.031	0.228	0.012	0.024	0.012	0.016	0.012	0	1.019	97.23
6061 Limits	0.4 - 0.8	0.7	0.15 -0.4	0.15	0.04 - 0.35	-	0.25	0.15	-	-	-	0.8 - 1.2	Bal.

Table III

CHEMICAL ANALYSIS OF CONDENSATE WATER USED IN CORROSION TESTING

Major Elements	Concentration, ppm
Calcium	1.812
Magnesium	0.423
Manganese	0.131
Zinc	0.493
Iron	0.021
Sodium	7.577
Phosphorus	4.904
Silicon	0.557

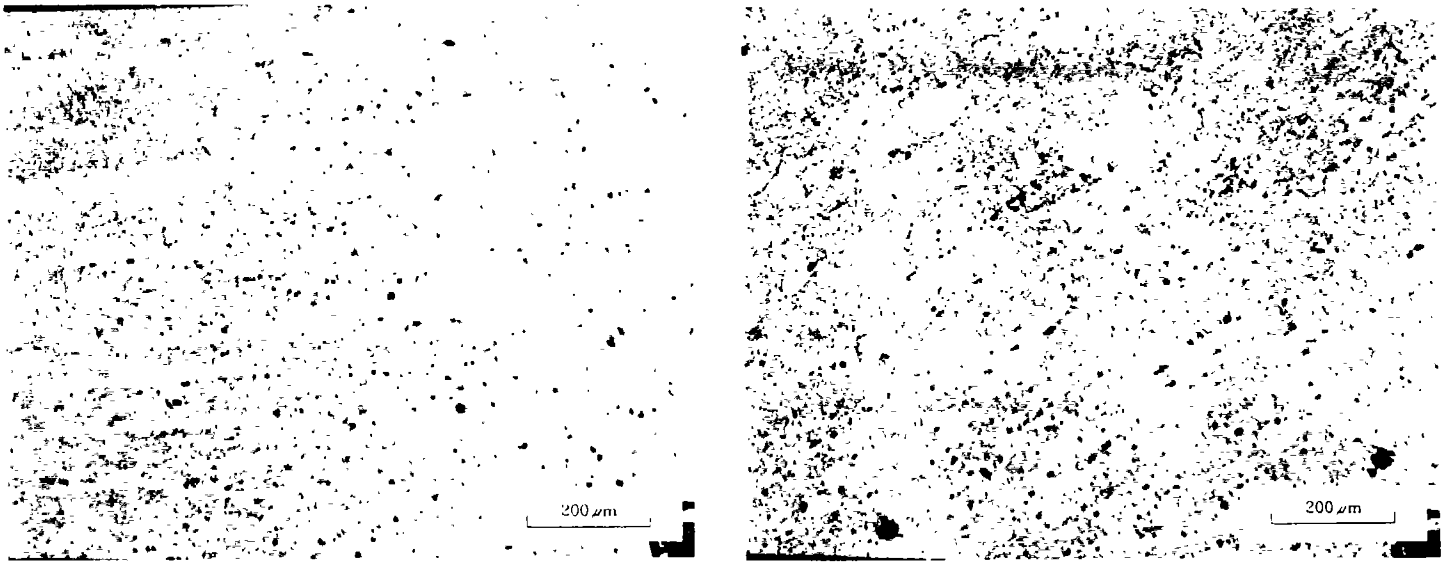
Anion	Concentration, ppm
Cholride	1.25
Formate	2.85
Nitrate	<1.5
Sulfate	7.49

Conductivity µmohs	0.052
Acidity (ph)	6.80

Table IV

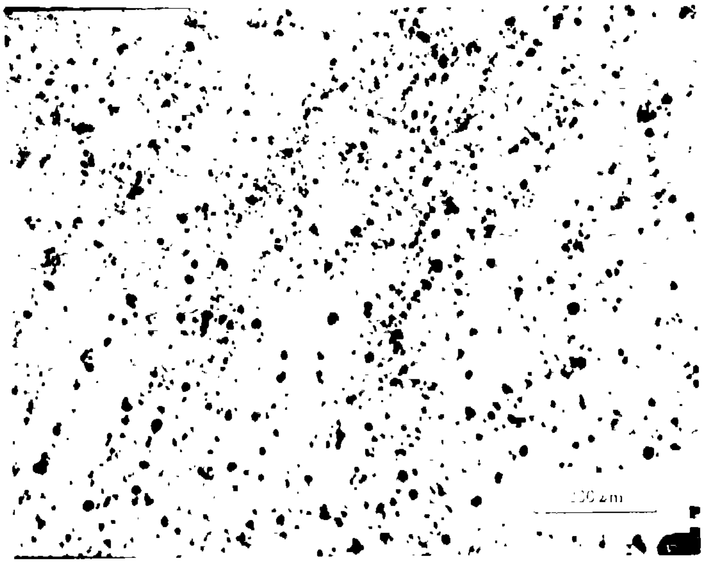
PARAMETERS FOR ARRHENIUS-POWER LAW CORROSION MODEL
($w = Ae^{-Qn/RT} t^n$) IN WATER VAPOR AT 100% RH.

Alloy	A ($\mu g/dm^2$)/hr^n	Qn/RT(K)	n
1100	7.37×10^7	4500	0.4086
5052	2.81×10^8	5600	0.5481
6061	5.45×10^6	3600	0.4532



(a) 1100 Aluminum Alloy

(b) 5052 Aluminum Alloy



(c) 6061 Aluminum Alloy

Figure 1. Optical Photomicrographs of As-Received 1100 5052, and 6061 Aluminum Alloys.

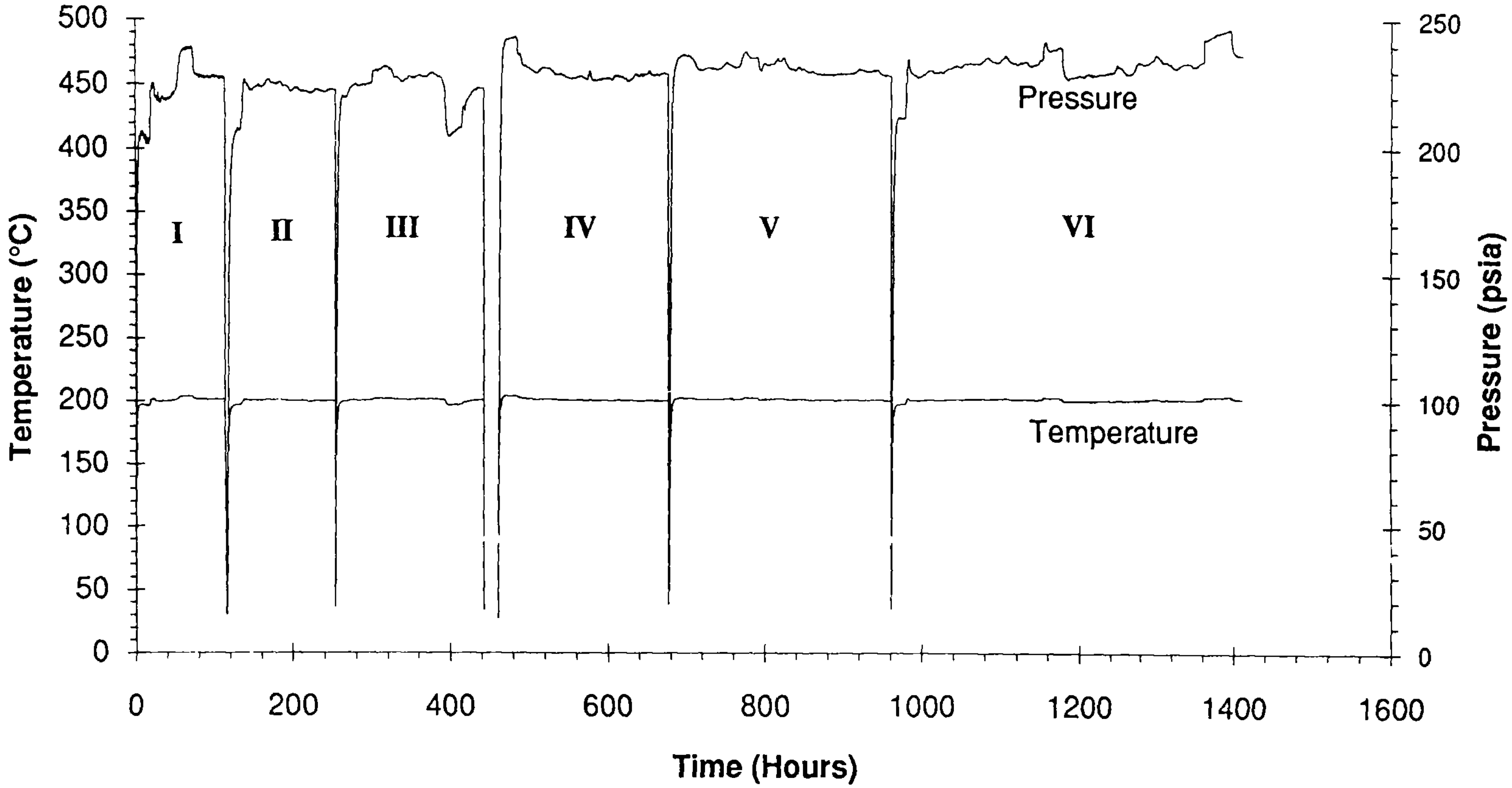


Figure 2. Typical Pressure and Temperature Chart for Corrosion Testing in the Autoclave.

100 hrs. 230 hrs. 425 hrs. 640 hrs. 900 hrs. 1400 hrs.

Figure 3. Typical Aluminum Alloy Coupons After Corrosion Testing in the Autoclave at 200 °C and 100% Relative Humidity.

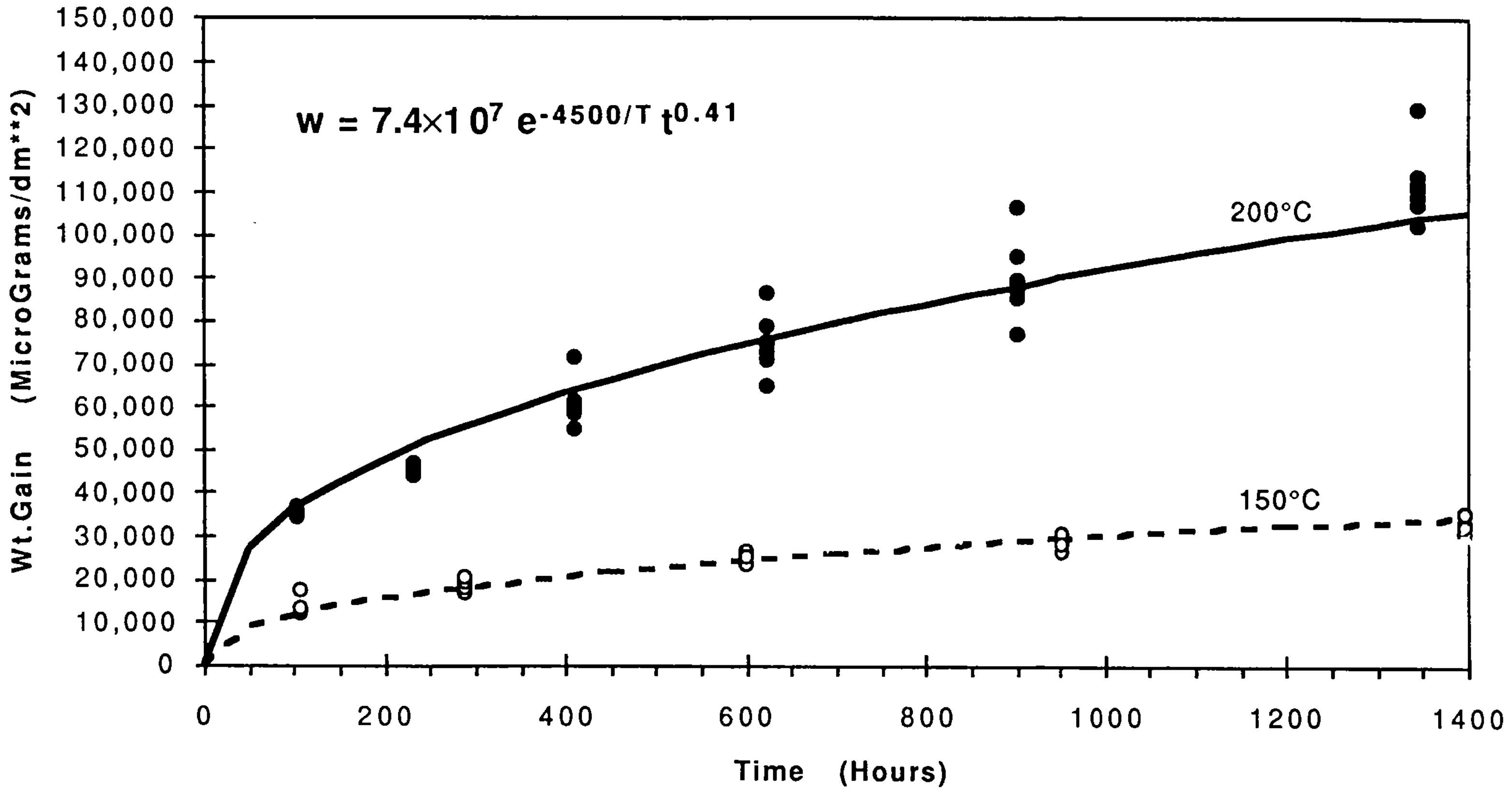


Figure 4. Weight Gain Data as a Function of Exposure Time for 1100 Aluminum Alloy at 100% Relative Humidity.

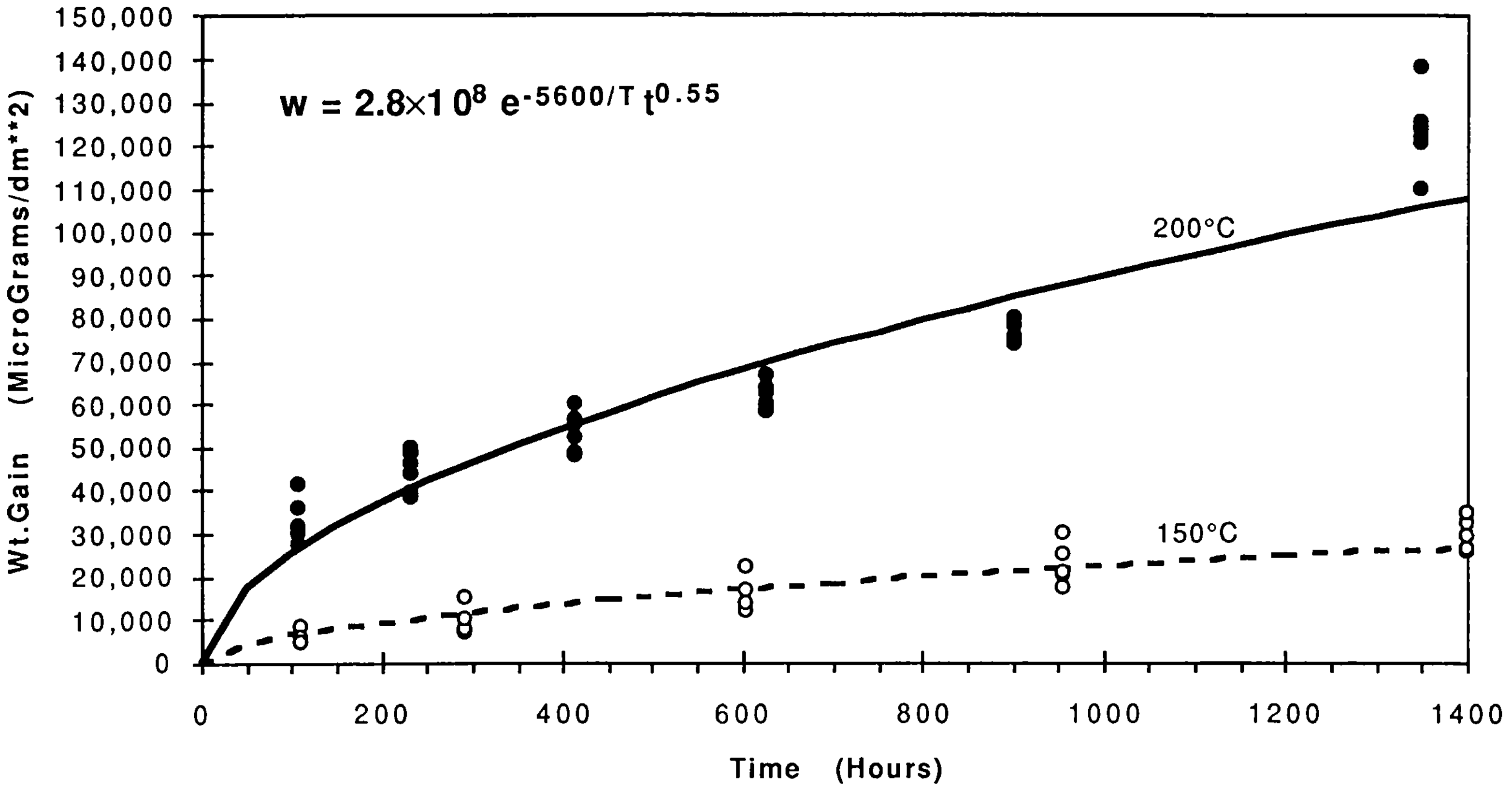


Figure 5. Weight Gain Data as a Function of Exposure Time for 5052 Aluminum Alloy at 100% Relative Humidity.

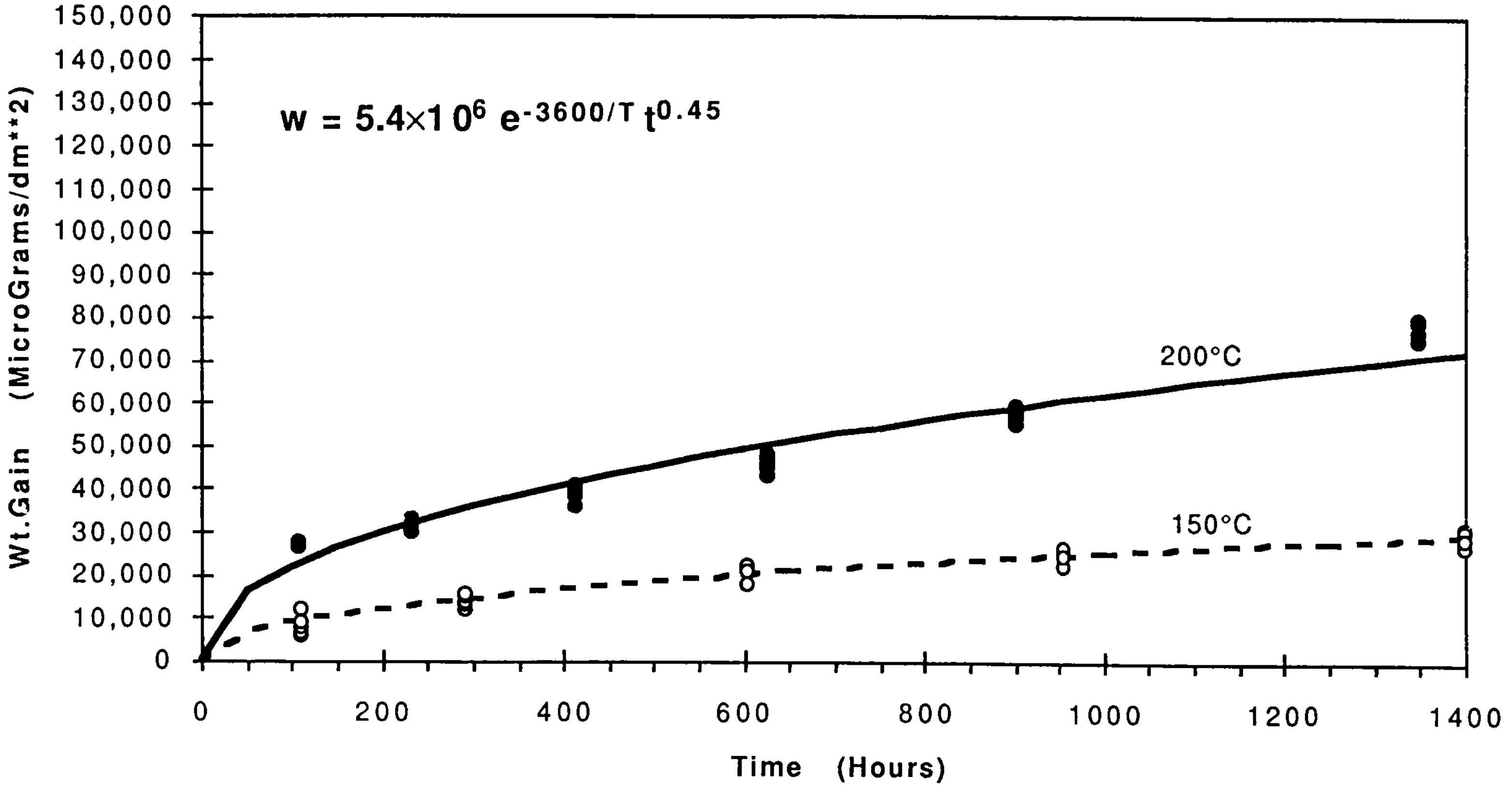


Figure 6. Weight Gain Data as a Function of Exposure Time for 6061 Aluminum Alloy at 100% Relative Humidity.

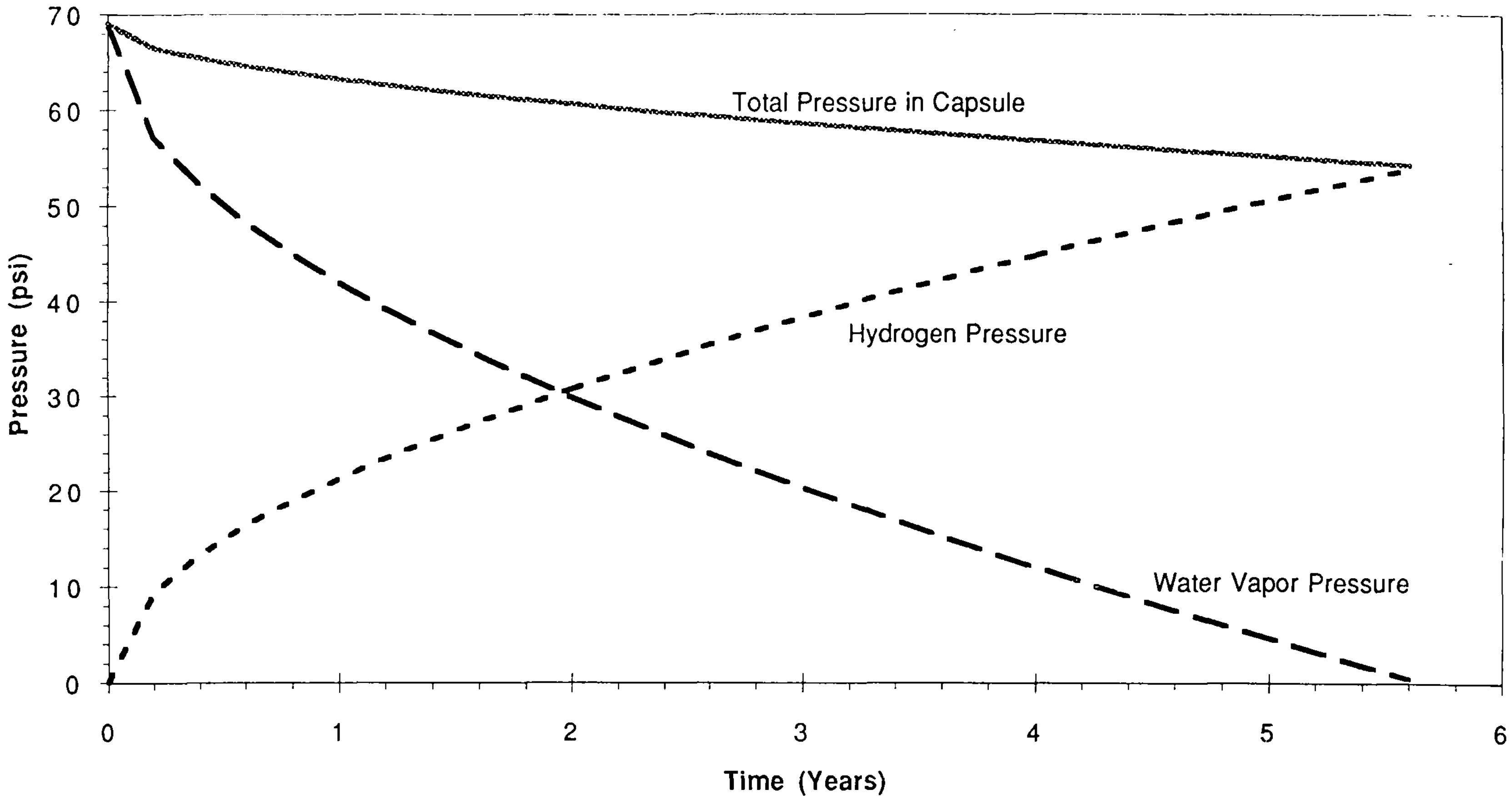


Figure 7. Changes in Water Vapor Pressure and Hydrogen Pressure due to Corrosion Reactions with Aluminum Inside a Closed System.

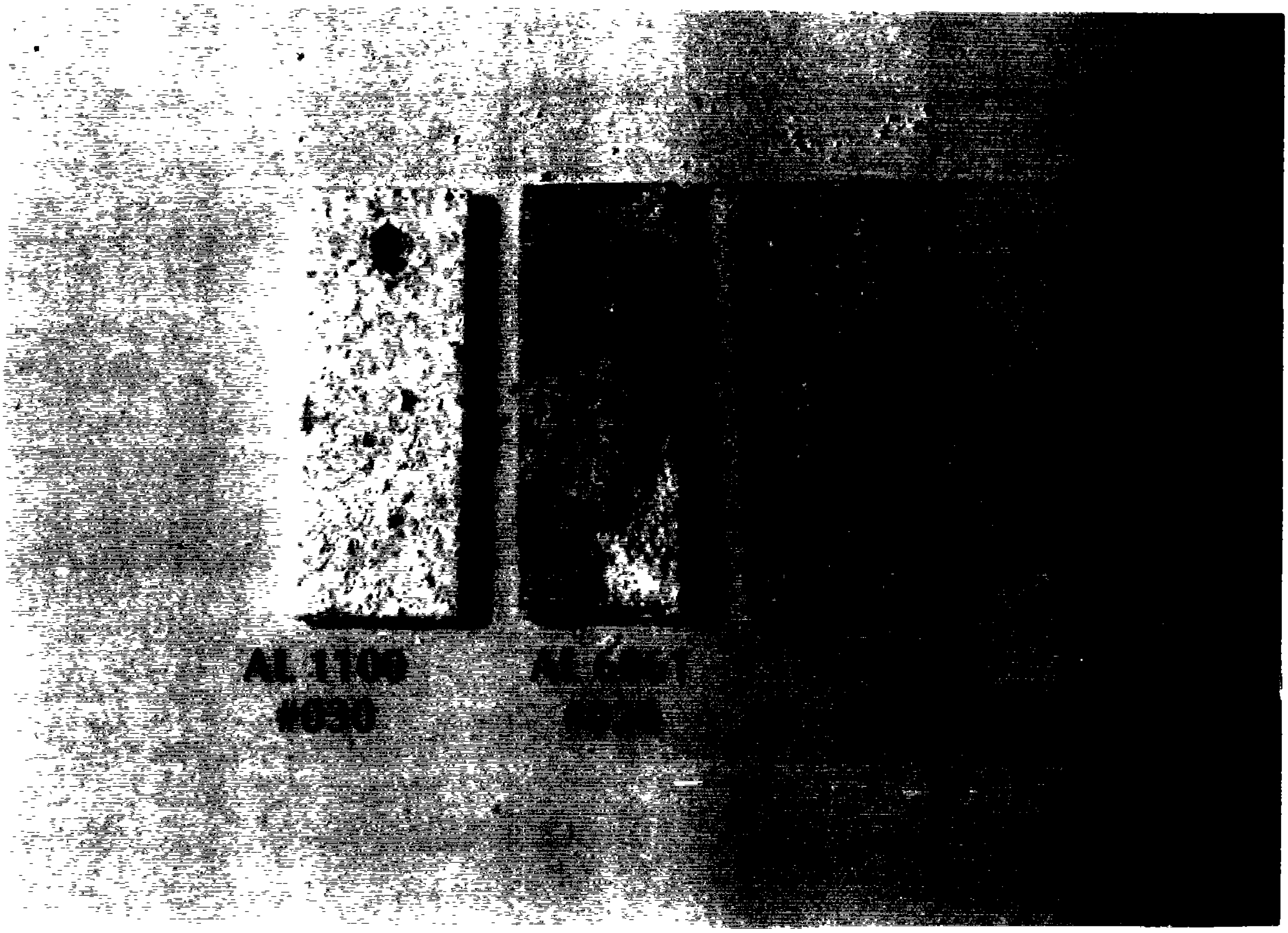


Figure 8. Corrosion of 1100, 5052, and 6061 Aluminum Alloys After 1 Week in a Humid Atmosphere containing NO_x Gases at 150 °C.