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## METHODS TO CALCULATE CORROSION RATES FOR ALLOY 22 FROM POLARIZATION RESISTANCE EXPERIMENTS

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### ABSTRACT

The general corrosion rate may be measured using immersion tests or electrochemical tests. Electrochemical tests are fast and can be used for a rapid screening of environmental effects such as temperature and electrolyte composition. Electrochemical tests are described in ASTM standards G 59 and G 102. The basis of these tests is to calculate the resistance to polarization ( $R_p$ ) in a voltage vs. current plot and to convert these values to corrosion rates using Faraday's law. Commercial software can calculate the corrosion rate based on inputs from the operator. This paper discusses three ways of calculating the corrosion rate (Methods 1, 2, and 3) based on a fixed set of acquired data of voltage vs. current. It is concluded that the way the corrosion rate is calculated does not greatly impact the absolute value of the corrosion rate. Variations in the acquired data (current, potential) from one experiment to another seem more important than the manner in which data is fitted with the  $R_p$  slope.

Keywords: N06022, Corrosion Rate, Polarization Resistance, Methods to Calculate Corrosion Rate

### INTRODUCTION

Alloy 22 (N06022) is a corrosion-resistant nickel based alloy [1] that was proposed as the external layer for the nuclear waste containers in Yucca Mountain. [2] Alloy 22 may suffer several types of degradation, including general corrosion. [2]

General corrosion or uniform corrosion is "corrosion that proceeds at about the same rate over a metal surface" as defined

by the ASTM Standard G 15 [3]. The corrosion rate of metals such as Alloy 22 is influenced by metallurgical and environmental factors. These include surface condition, temperature, pH of the electrolyte in contact with the alloy, exposure time, etc. Under most conditions Alloy 22 will remain passive, that is, a protective  $Cr_2O_3$  will form on the surface slowing down the dissolution rate of the underlying metal. As the exposure time to the corroding environment increases the general corrosion rate decreases. This is a well-established fact for passive materials, including Alloy 22 [4].

The corrosion rate is generally calculated in the industry by weight (mass) loss [5,6]. Guidelines for mass loss corrosion rate determination are given in the ASTM Standard G 31 and G 1 [3]. The measurement of corrosion rate by weight loss (WL) is more accurate when the environment is aggressive and the mass losses are easily measured during laboratory testing. In the mass-loss procedure, pre-weighed coupons of the alloy to be tested are exposed to the corrosive environment for a given period of time. At the end of the testing time, the coupons are cleaned, dried and weighed. The corrosion rate is calculated dividing the mass loss by the surface area of each coupon ( $A$ ), the exposure time ( $t$ ) and the density of the alloy ( $d$ ) (Eq. 1)

$$CR \left( \frac{\mu m}{year} \right) = \frac{8.76 \cdot 10^7 (W_i - W_f)(g)}{A(cm^2) \cdot t(h) \cdot d(g \cdot cm^{-3})} \quad (1)$$

where  $W_i$  and  $W_f$  are the initial and final mass of the coupon in grams.

The corrosion rate can also be calculated using electrochemical methods such the polarization resistance (PR) method described in ASTM G 59 and G 102 [3,5,6]. Each of these polarization resistance tests lasts approximately four minutes. An initial potential of 20 mV below the corrosion potential ( $E_{\text{corr}}$ ) is ramped to a final potential of 20 mV above  $E_{\text{corr}}$  at a rate of 0.167 mV/s. The Polarization Resistance ( $R_p$ ) is defined as the slope of the potential (E) vs. current density (i) at  $i = 0$  (ASTM G 59) [3].

$$R_p = \left( \frac{\partial \Delta E}{\partial i} \right)_{i=0, dE/dt \rightarrow 0} \quad (2)$$

where  $\Delta E = E - E_{\text{corr}}$ . The corrosion current density,  $i_{\text{corr}}$ , is related to the polarization resistance  $R_p$  (in Ohm-cm<sup>2</sup>) by the Stern-Geary coefficient B (ASTM G 59)

$$i_{\text{corr}} = \frac{B}{R_p} \quad B = \frac{b_a \cdot b_c}{2.303(b_a + b_c)} \quad (3)$$

where  $i_{\text{corr}}$  is in A/cm<sup>2</sup> and B is in V.  $b_a$  and  $b_c$  are the anodic and cathodic Tafel slopes in V

$$i_{\text{corr}} = \frac{1}{R_p} \times \frac{b_a \cdot b_c}{2.303(b_a + b_c)} \quad (4)$$

The corrosion rate can then be calculated using the Faraday equation (ASTM G 59)

$$CR(\mu\text{m}/\text{yr}) = k \frac{i_{\text{corr}}}{d} EW \quad (5)$$

Where k is a conversion factor ( $3.27 \times 10^6 \mu\text{m} \cdot \text{g} \cdot \text{A}^{-1} \cdot \text{cm}^{-1} \cdot \text{yr}^{-1}$ ),  $i_{\text{corr}}$  is the corrosion current density in  $\mu\text{A}/\text{cm}^2$  (calculated from the measurements of  $R_p$ ), EW is the equivalent weight, and d is the density of Alloy 22 (8.69 g/cm<sup>3</sup>). Assuming an equivalent dissolution of the major alloying elements as Ni<sup>2+</sup>, Cr<sup>3+</sup>, Mo<sup>6+</sup>, Fe<sup>2+</sup>, and W<sup>6+</sup>, the EW for Alloy 22 is 23.28 (ASTM G 102) [3].

## POLARIZATION RESISTANCE

The polarization resistance ( $R_p$ ) is defined as the slope of a potential (E) (Y-axis) vs. Current (I) (X-axis) plot in the vicinity of the corrosion potential ( $E_{\text{corr}}$ ) or when the applied current is nearing zero (Eq. 2). When the potential is ramped and the current is measured, E is the independent variable and I is the dependent variable. In a proper mathematical plot, E should be represented in the X-axis and I in the Y-axis. However, in the conventions of the corrosion community, E is always plotted in the Y-axis and I in the X-axis. Therefore, how this plot of  $\Delta E/\Delta I$  is analyzed is sometimes a matter of debate.

Commercial software allows for the data to be represented and calculated as E vs. I or I vs. E. The commercial software also can calculate the slope ( $R_p$  or  $1/R_p$ ) and the corrosion rate according to the limits (range) that the operator puts to the collected data. The commercial software also allows for the operator to draw a free hand slope to visually fit the data. Then the software calculates the slope based on this free drawn line.

## PURPOSE OF THIS PAPER

This paper was prepared to document ways of calculating corrosion rates from electrochemical measurements according to ASTM G 59. The purpose was to have different operators do the calculations of  $R_p$  (or corrosion rate) using three different methods and to compare the results and the validity of each method. All three analyses are generated by using Gamry Echem Analyst 1.3 software.

Method 1: Using the commercial software with the Applied Voltage plotted on the Y-Axis and the resultant Current plotted on the X-axis. This may not be the most valid of the three methods since it fits the slope against the rules of linear regression analysis, which requires the plotting the Voltage in the X-axis as the independent variable. But this method is used since the plot is the typical Corrosion Engineering type of plot (Figure 1).

Method 2: Using the commercial software with the Current plotted on the Y-Axis and the Voltage plotted on the X-axis. This is the proper method, mathematically.

Method 3: Using the commercial software calculation routine which allows the user to draw an interactive on-screen slope line in the on-screen plot of the polarization resistance data. The software then calculates the slope of this manually inserted line. Using this slope value, the operator can then use an Excel spreadsheet and appropriate equations to calculate a corrosion rate based on the slope. The proportionality constant was calculated assuming the equivalent weight of Alloy 22 to be 23.28, the density 8.69 g/cm<sup>3</sup>, and the Faraday constant 96,485 C/mol. For Alloy 22, an  $R_p$  value of 1 M $\Omega$ .cm<sup>2</sup> yields a corrosion rate of 0.228  $\mu\text{m}/\text{year}$ .

The fittings using Methods 1 and 2 were carried out using the range of potentials  $\pm 10$  mV with respect to the corrosion potential ( $E_{\text{corr}}$ ). The fitting for Method 3 was at the discretion of the operator, generally using the straight part of the acquired data. The experimental results are presented either as polarization resistance ( $R_p$ ) in Ohm.cm<sup>2</sup> or as corrosion rates (CR) in  $\mu\text{m}/\text{year}$ . These two quantities are inversely proportional to each other, that is, the higher the  $R_p$  the lower the CR (Eqs. 2 and 5). The use of  $R_p$  to "represent" corrosion rate sometimes is convenient since the Tafel slopes values are not necessary to be known. In the current paper, when CR was calculated the Tafel slopes were assumed to be  $\pm 120$  mV.

## EXPERIMENTAL RESULTS

Figures 1-3 show the data as visualized by the commercial software for specimen DEA2843, an Alloy 22 rod immersed in 0.1 M oxalic acid solution at 30°C. Three polarization resistance tests were carried out on 29Mar04 and Figures 1-3 show the data for the second run (called LP-2). Figure 1 is the representation of the fitting using Method 1 (putting the potential in the Y-axis as is customary in the corrosion community). Figure 2 is the calculation using Method 2 (putting the Potential in the X-axis as it would be proper for a mathematical linear regression). Figure 3 shows the representation with a manual fit of the curve or Method 3.

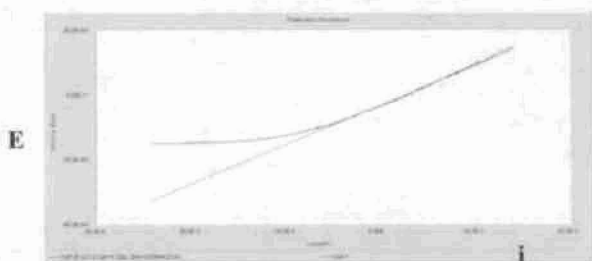


Figure 1. LP-2 for Specimen DEA2843, Tested 29Mar04 in 0.1 M Oxalic Acid, 30C. Method 1.

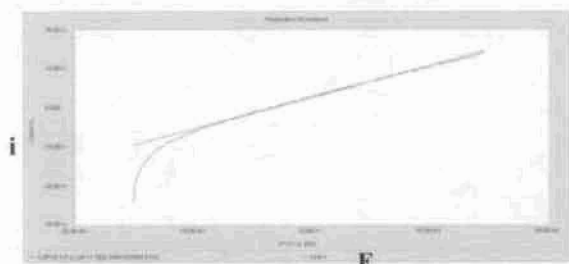


Figure 2. LP-2 for Specimen DEA2843, Tested 29Mar04 in 0.1 M Oxalic Acid, 30C. Method 2.

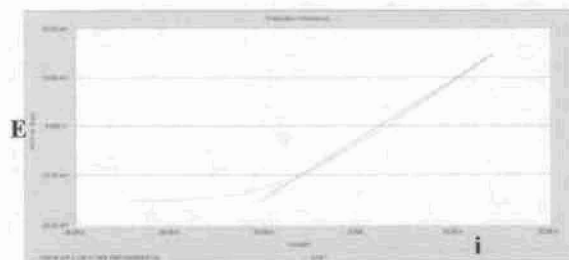


Figure 3. LP-2 for Specimen DEA2843, Tested 29Mar04 in 0.1 M Oxalic Acid, 30C. Method 3.

Table 1 shows the calculated corrosion rate values using all three methods. On the specified date, three consecutive polarization resistance tests were carried out for DEA2843 (LP-1, LP-2 and LP-3). Table 1 shows that the corrosion rate was practically the same for the three methods. Methods 1 and 2 only agree because the data was clean (not "noisy") and the data was rather linear in the range of potentials where corrosion rate was calculated. For "noisy" data the values of corrosion rates from Methods 1 and 2 may differ by one order of magnitude.

Table 1. Three Methods to Calculate the Corrosion Rate of Alloy 22

29Mar04 (3 Tests)	Corrosion Rate in $\mu\text{m}/\text{year}$ of Alloy 22, DEA2843 Rod in 0.1 M Oxalic Acid at 30C		
	Method 1	Method 2	Method 3
LP-1	0.216	0.212	0.195
LP-2	0.187	0.186	0.188
LP-3	0.192	0.192	0.189
Average	0.198	0.197	0.198
Standard Deviation	0.016	0.014	0.004

### Testing of Alloy 22 in MIC Experiments

Three welded discs of Alloy 22 were exposed to an electrolyte solution ten times more concentrated than well water (10X J-13) plus a glucose nutrient at ambient temperature in three different vessels (V10, V11 and V12). The solution was inoculated with Yucca Mountain type microorganisms (Non-Sterile conditions) to study the microbiologically influenced corrosion (MIC) of Alloy 22. The Polarization Resistance ( $R_p$ ) was calculated using the commercial software with current in the Y-axis and potential in the X-axis (Method 2) as well as using a manual fit (Voltage in Y-axis and current in the X-axis) as in Method 3. The  $R_p$  values are plotted in Figure 4 as a function of a sequence number. The sequence number increases with the immersion time in the vessels. However, the time interval is not the same between sequence numbers. There are two or three  $R_p$  values for each vessel for each sequence number. Figure 4 shows that the  $R_p$  is approximately the same using both Methods 2 and 3. Taking an overall average of the  $R_p$  values for each method for all the sequence numbers in Figure 4, the average  $R_p$  values are 17.81 for Method 2 and 18.06 for Method 3. These are practically the same. The standard deviation was 25.95 for Method 2 and 17.51 for Method 3. That is, doing the  $R_p$  slope manually results is less error than using the commercial software fitting.

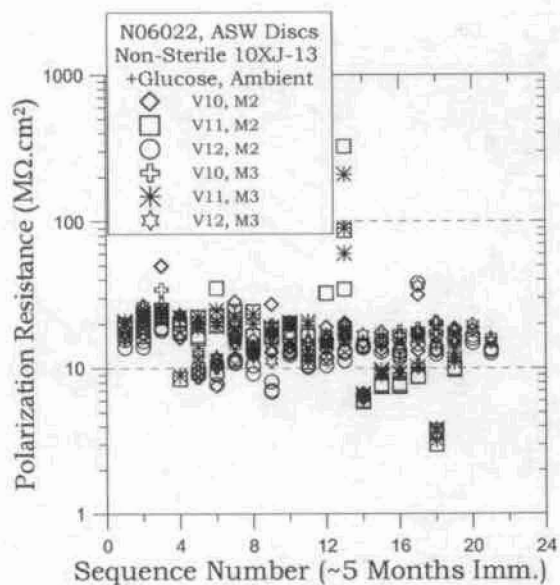


Figure 4. Polarization Resistance in Non-Sterile Environment using Methods 2 and 3

### Long Term Immersion of Alloy 22 Rods

Figure 5 shows the corrosion rate of a MA Alloy 22 specimen (Rod DEA2843) as a function of immersion time in 0.1 M oxalic acid solution at 30°C. Results were analyzed using Methods 1, 2 and 3 (M1, M2 and M3 in Figure 5). For each immersion time, there were three values of corrosion rates corresponding to three sequential runs (run 1 = LP-1, run 2 = LP-2 and run 3 = LP-3). The corrosion rate was approximately constant in time and between 0.15  $\mu\text{m}/\text{year}$  and 0.3  $\mu\text{m}/\text{year}$ . Table 1 shows the average corrosion rate for the specimen at a fixed time according to each method of evaluation. The average corrosion rate was approximately the same at 0.2  $\mu\text{m}/\text{year}$  independently of the method used for calculation. The lowest standard deviation (SD) corresponded to Method 3 (Manual Fitting) and the largest to Method 1 (E in Y-axis and current in X-axis).

Table 2 shows the average corrosion rate using the three methods of the MA Alloy 22 specimen DEA3087, which was immersed for hundreds of days in naturally aerated 1 M  $\text{CaCl}_2$  + 1 M  $\text{Ca}(\text{NO}_3)_2$  solution at 90°C. The average corrosion rate is for a total of three measurements at each testing time. The standard deviation (SD) values are also reported. Figure 6 shows a representation of the corrosion rates only for Methods 2 and 3. The value of corrosion rates using Method 1 was not included in Figure 6 since it had a large standard deviation at the highest time, therefore overshadowing the rest of the data in the figure. Method 3 generated the lowest corrosion rates; however, Figure 6 shows that the values were comparable to

the ones generated using Method 2. The tendency of a decrease in the corrosion rate as the time increased was the same for Methods 2 and 3. Table 2 shows that the largest standard deviation corresponded to Method 1 and the lowest to Method 3 (Manual Fit).

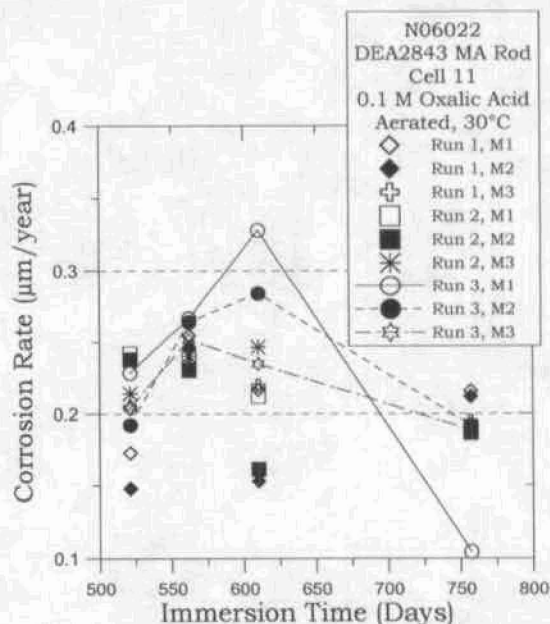


Figure 5. Corrosion Rate of Alloy 22 in oxalic acid using the 3 Methods

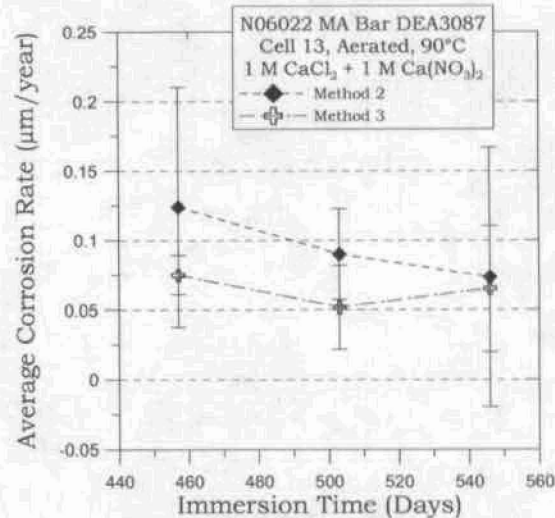


Figure 6. Corrosion Rates of Alloy 22 in 1 M  $\text{CaCl}_2$  + 1 M  $\text{Ca}(\text{NO}_3)_2$  at 90°C

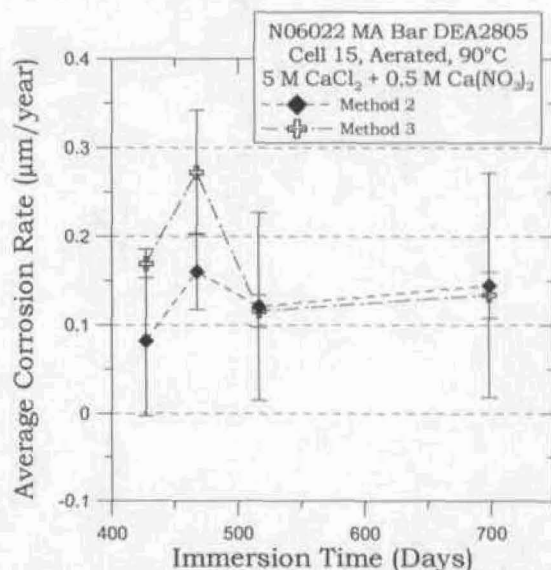
**Table 2. Corrosion Rate of Alloy 22 (Rod DEA3087) in 1 M CaCl<sub>2</sub> + 1 M Ca(NO<sub>3</sub>)<sub>2</sub> at 90°C**

Date Cell 13	Immersion Time (Days)	Corrosion Rate (µm/year) ± Standard Deviation		
		Method 1	Method 2	Method 3
31Jul03	457	0.511 ± 0.496	0.124 ± 0.086	0.075 ± 0.014
15Sep03	503	0.143 ± 0.049	0.090 ± 0.033	0.052 ± 0.030
28Oct03	546	-0.080 ± 1.100	0.074 ± 0.093	0.065 ± 0.045

Table 3 shows the average corrosion rate using the three methods of the MA Alloy 22 specimen DEA2805, which was immersed for long time in 5 M CaCl<sub>2</sub> + 0.5 M Ca(NO<sub>3</sub>)<sub>2</sub> solution at 90°C. The average corrosion rate is for a total of three measurements at each testing time. The standard deviation (SD) values are also reported. Figure 7 shows a representation of the corrosion rates only for Methods 2 and 3. The value of corrosion rates using Method 1 was not included in Figure 7 since it had a large standard deviation and negative corrosion rate at the first testing time, therefore overshadowing the rest of the data in the figure. Negative corrosion rates have no physical significance and are a result of noisy electrochemical measurements. For the testing times between 467 days and 698 days, the corrosion rate among all three methods (especially Methods 2 and 3) were similar (Table 3), independently of the immersion time and approximately 0.15 µm/year. Method 3 generated the lowest standard deviation (SD) of the three methods (Figure 7 and Table 3).

**Table 3. Corrosion Rate of Alloy 22 (Rod DEA2805) in 0.5 M CaCl<sub>2</sub> + 0.5 M Ca(NO<sub>3</sub>)<sub>2</sub> at 90°C**

Date Cell 15	Immersion Time (Days)	Corrosion Rate (µm/year) ± Standard Deviation		
		Method 1	Method 2	Method 3
30Jul03	427	-3.40 ± 7.013	0.082 ± 0.085	0.169 ± 0.016
08Sep03	467	0.234 ± 0.008	0.160 ± 0.043	0.272 ± 0.070
27Oct03	516	0.253 ± 0.785	0.121 ± 0.106	0.116 ± 0.018
26Apr04	698	0.318 ± 0.129	0.145 ± 0.127	0.134 ± 0.026



**Figure 7. Corrosion Rates of Alloy 22 in 0.5 M CaCl<sub>2</sub> + 0.5 M Ca(NO<sub>3</sub>)<sub>2</sub> at 90°C (Cell 15)**

Figure 8 shows the calculation of the corrosion rates of Alloy 22 immersed in Simulated Acidified Water (SAW) without silicates in the solution (Cell 17 in the long term monitoring of E<sub>corr</sub>). This solution was naturally aerated and maintained at 90°C. Figure 8 shows the corrosion rate data between the immersion times of 180 days and 402 days for three types of materials: (1) Mill Annealed (MA) rod (DEA2813), (2) As-Welded (ASW) rod (JE2042) and (3) Welded Plus Thermally Aged (WPA) rod (JE2014). The thermal aging of JE2014 was carried at 700°C for 173 h. All three methods show that the corrosion rate of Alloy 22 increased as the immersion time increased. No explanation is offered at this time for this phenomenon since it is beyond the purpose of this paper. It is expected that for a passivating metal such as Alloy 22, the corrosion rate will decrease as the testing time increased. Figure 8 also shows that the corrosion rate of the MA material was the highest and the corrosion rate of the ASW material was the lowest. These results seem consistent and no explanation is offered at this time either. More importantly for this paper, Figure 8 shows that the corrosion rate of each type of Alloy 22 material was practically the same using either one of the three methods of calculation analyzed here. Method 1 yielded, in general, the highest corrosion rate but results from Methods 2 and 3 were basically identical. Considering all three materials for the four tested times, the lowest standard deviation corresponded to Method 3 and the highest for Method 1.

Figure 9 and Table 4 show the corrosion rate for three Alloy 22 specimens, MA DEA2816, ASW JE2045 and WPA JE2017. Table 4 also shows the standard deviation of three



measurements of corrosion rate at each time for each specimen. The largest variation in the corrosion rate in Figure 9 corresponded to values calculated using Method 1. This method also yielded the largest standard deviation (Table 4).

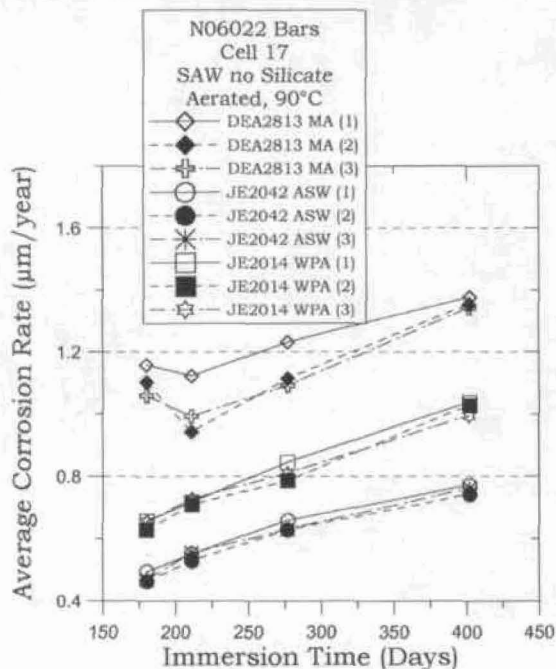


Figure 8. Corrosion Rates of Alloy 22 in SAW No-Silicate, 90°C (Cell 17)

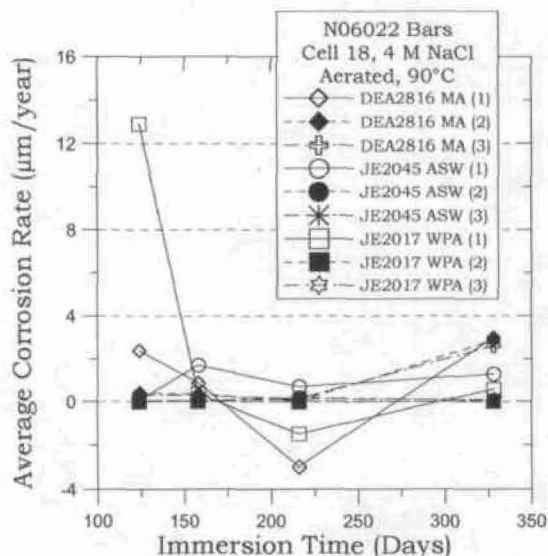
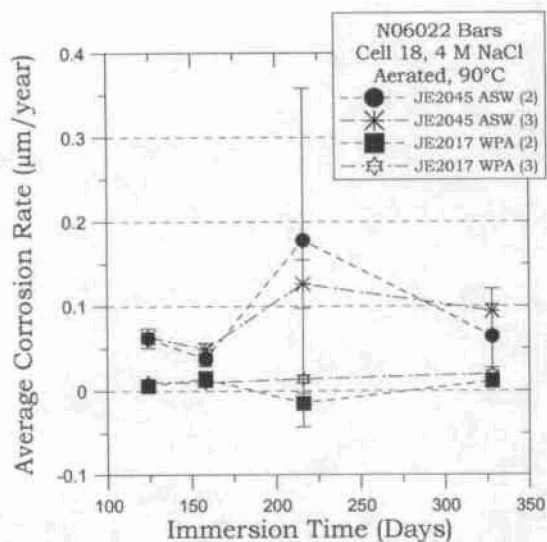


Figure 9. Corrosion Rate of Alloy 22 in 4 M NaCl at 90°C (Cell 18).

Figure 10 shows the corrosion rate of Alloy 22 in 4 M NaCl at 90°C for ASW and WPA specimens. The lowest corrosion rate corresponded to the WPA specimen. Figure 10 also shows that the corrosion rates values calculated using Methods 2 and 3 were similar to each other for each specimen. Method 3 yielded the lowest standard deviation (Table 4 and Figure 10). Table 4 shows that Method 2 could produce negative corrosion rates in cases of noisy data.

Table 4. Corrosion Rate of Alloy 22 in 4 M NaCl, 90°C

Date Cell 18	Immersion Time (Days)	Corrosion Rate (µm/year) ± Standard Deviation		
		Method 1	Method 2	Method 3
<b>MA DEA2816</b>				
23Jul03	124	2.387 ± 1.407	0.422 ± 0.248	0.315 ± 0.009
26Aug03	158	0.884 ± 0.086	0.351 ± 0.175	0.293 ± 0.041
23Oct03	216	-2.995 ± 8.995	0.026 ± 0.062	0.146 ± 0.015
12Feb04	328	2.979 ± 4.431	2.860 ± 4.388	2.611 ± 3.774
<b>ASW JE2045</b>				
23Jul03	124	0.0789 ± 0.011	0.062 ± 0.012	0.064 ± 0.004
26Aug03	158	1.708 ± 1.562	0.037 ± 0.008	0.049 ± 0.007
23Oct03	216	0.708 ± 0.595	0.178 ± 0.181	0.127 ± 0.029
12Feb04	328	1.294 ± 1.844	0.065 ± 0.037	0.094 ± 0.027
<b>WPA JE2017</b>				
23Jul03	124	12.895± 22.278	0.006 ± 0.004	0.010 ± 0.002
26Aug03	158	0.365 ± .0554	0.014 ± 0.009	0.010 ± 0.005
23Oct03	216	-1.496 ± 1.933	-0.014 ± 0.028	0.014 ± 0.004
12Feb04	328	0.586 ± 0.932	0.011 ± 0.007	0.020 ± 0.000



**Figure 10.** Corrosion Rate of Alloy 22 in 4 M NaCl at 90°C (Cell 18) using Methods 2 and 3 for ASW and WPA specimens

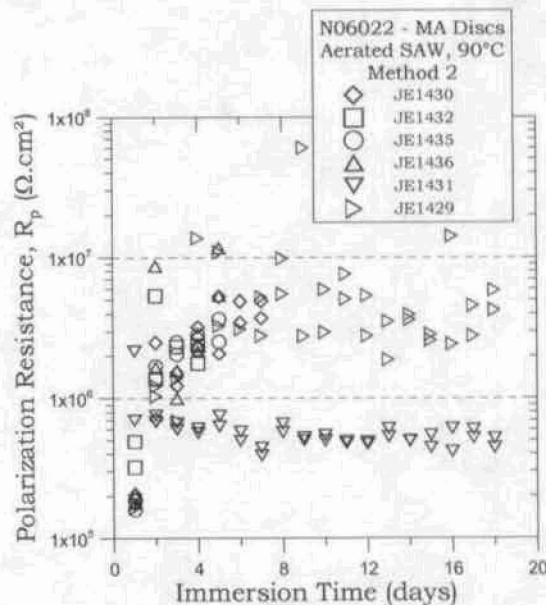
### Corrosion Behavior of Alloy 22 MA discs in Aerated SAW at 90°C

The corrosion behavior of Alloy 22 discs in aerated SAW solution at 90°C was evaluated as a function of time for six specimens. Figure 11 shows the polarization resistance ( $R_p$ ) using Method 2 for the six specimens as a function of the immersion time in the solution. There are two  $R_p$  values for each specimen for each testing time. In general, for the few first days of immersion,  $R_p$  increased as the time increased. However, there were two specimens (JE1429 and JE1431) for which the  $R_p$  showed the largest discrepancy. Figure 11 shows that using a single method of calculating the individual polarization resistances (Method 2) can yield a wide variety of results from test to test, i.e. varying from specimen to specimen at each testing time. Figure 12 and Table 5 show the average corrosion rates for the six specimens listed in Figure 11 for the first five days of immersion using all three methods. Table 5 also lists the standard deviation in the corrosion rate considering all six specimens at each immersion time. Method 1 yielded higher corrosion rates than Method 2, even though the trend is the same. The average corrosion rates values between Methods 2 and 3 are practically indistinguishable (Figure 12). The lowest standard deviation corresponded to Method 3 (Table 5).

**Table 5.** Corr. Rate of Alloy 22 in aerated SAW, 90°C

Immersion Time (Days)	Corrosion Rate ( $\mu\text{m}/\text{year}$ ) $\pm$ Standard Deviation		
	Method 1	Method 2	Method 3
1	1.236 $\pm$ 0.298	0.962 $\pm$ 0.445	0.527 $\pm$ 0.081
2	0.708 $\pm$ 0.448	0.177 $\pm$ 0.102	0.222 $\pm$ 0.067
3	0.399 $\pm$ 0.124	0.193 $\pm$ 0.103	0.170 $\pm$ 0.094
4	0.452 $\pm$ 0.591	0.141 $\pm$ 0.125	0.143 $\pm$ 0.111
5	0.417 $\pm$ 0.254	0.112 $\pm$ 0.120	0.087 $\pm$ 0.013

Average Corrosion Rate from Six Disc Specimens at each Immersion Time. Specimens: JE1430, JE1432, JE1435, JE1436, JE1431 and JE1429.



**Figure 11.** Polarization Resistance of Alloy 22 in aerated SAW at 90°C (Method 2)

### Corrosion Behavior of Alloy 22 in 6 m NaCl and 6 m NaCl + 0.9 m KNO<sub>3</sub> at 100°C

Figures 13 and 14 show the individual polarization resistance values for Alloy 22 as a function of immersion time in aerated 6 m NaCl and 6 m NaCl + 0.9 m KNO<sub>3</sub> solutions at 100°C, respectively. Five specimens were tested in each solution. The total immersion time was four days. Figures 13 and 14 show that in general, as the immersion time increased to

the second day the  $R_p$  increased. For both solutions the  $R_p$  was practically the same. Also, for each specimen at each testing time the value of  $R_p$  was practically the same using either Methods 1 or 2. At each testing time there was more variation in the corrosion rate between specimen and specimen than between method and method for each specimen (see for example data for Day 2 in either solution). Figures 15 and 16 show the average  $R_p$  values in the pure chloride and in the chloride plus nitrate solutions, respectively. The standard deviation of the data for the five specimens is also shown. Basically, the standard deviation is the same regardless of method used to calculate the  $R_p$ . Also, the average  $R_p$  is only slightly higher in the nitrate containing solution.

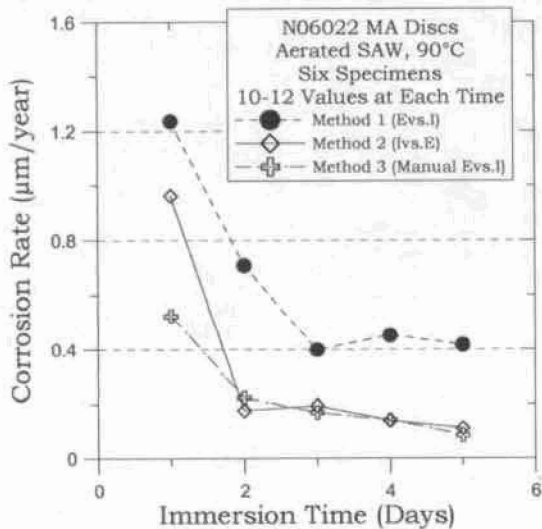


Figure 12. Average Corrosion Rates of Alloy 22 in aerated SAW at 90°C (Methods 1-3)

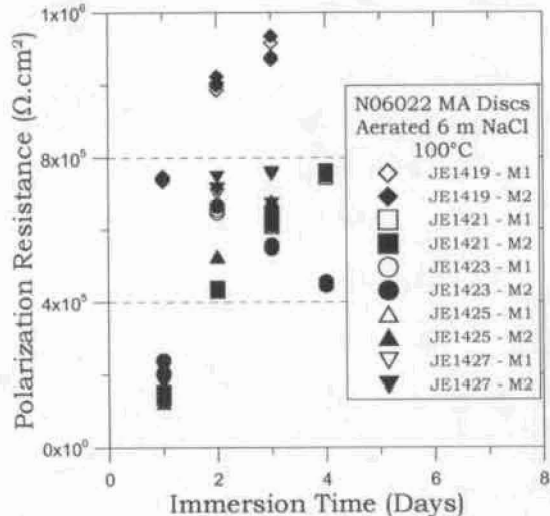


Figure 13. Polarization Resistance of Alloy 22 in aerated 6 m NaCl at 100°C

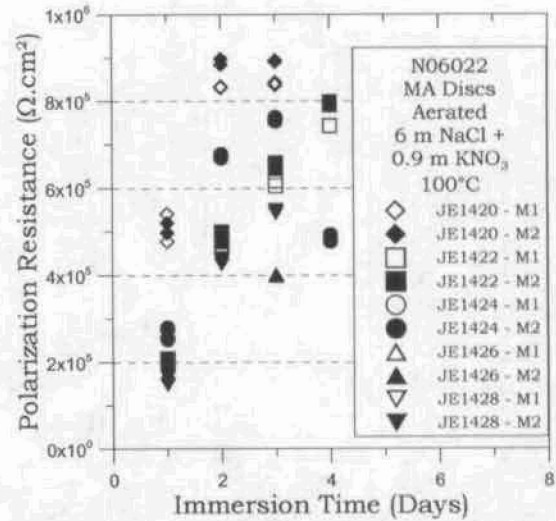


Figure 14. Polarization Resistance of Alloy 22 in aerated 6 m NaCl + 0.9 m  $KNO_3$  at 100°C

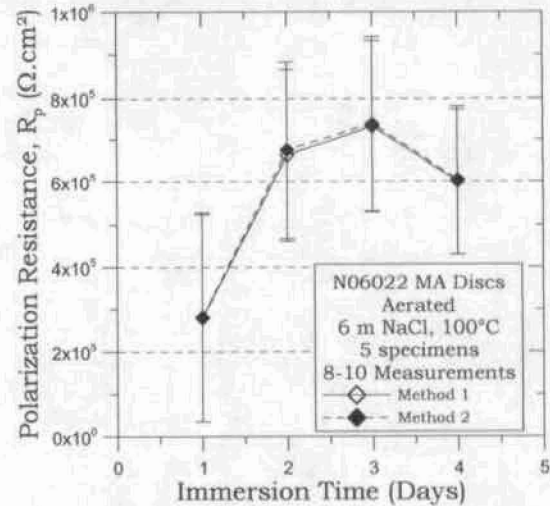


Figure 15. Average Polarization Resistance of Alloy 22 in aerated 6 m NaCl at 100°C

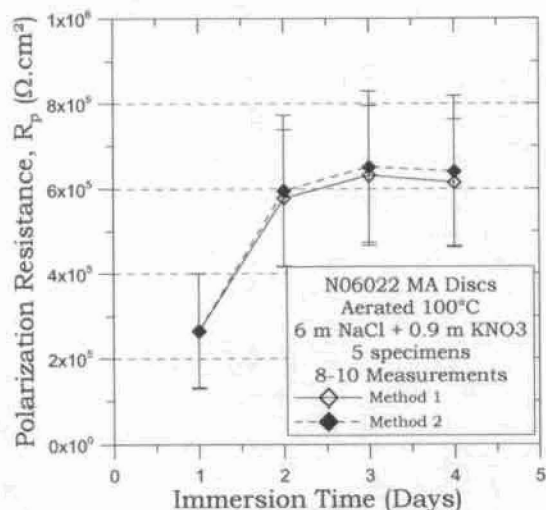
### Final Remarks

Three methods were presented here to illustrate the calculation of polarization resistance (corrosion rates) of Alloy 22 in a variety of environments. Method 1 is given for illustrative purposes only. Mathematically, the use of Method 1 to calculate  $R_p$  is not correct. However, this document shows that the values of polarization resistance obtained using Method 1 are not too far off the values obtained using either Method 2 (preferred) or Method 3, mainly because the measured data of E vs. I was not highly noisy. Method 1 often yields the highest corrosion rates and the largest standard deviations since the fitting of the data is not as adequate as using for example



Method 2. Nevertheless, data presented here shows that there is usually more variation in the corrosion rates between specimen and specimen tested under identical environmental conditions than between Method 1 and Method 2 for a single specimen and condition. Results from the current report shows that the trends (for example effect of immersion time) in corrosion rate using Methods 1 and 2 were the same. The results reported here pertain only to the specific specimens and testing conditions analyzed. Results obtained from Methods 1 and 2 will vary depending on the amount of the noise in the measured data.

The most reproducible results are obtained with either Method 2 or Method 3. Mathematically, Method 2 would be preferred to Method 3 since it can be easily reproduced by a second operator. Once the limits of potential (voltage) are set, the software calculates the corrosion rate. It is worth noting here the surprising results obtained using Method 3. Even though Method 3 is operator dependent, the same ranking of Method 3 was found with respect to Method 2 (operator independent) using results from three different operators. Operator 1 did the manual calculations of the MIC results, Operator 2 did the fittings for the Long Term Bench-Top Cells and Operator did the calculations of the Alloy 22 discs. The results from all three operators show that the results from Method 3 were extremely close to the results from Method 2. Method 3, in all cases, yielded the lowest standard deviation showing that the good eye of the operator generally surpasses the mathematical fitting of the current vs. potential equation, especially when there is noise in the acquired data. The problem with Method 3 is that the results cannot be precisely reproduced, even by the same operator. However, the error in Method 3 is still smaller than that in Method 2.



**Figure 16.** Average Polarization Resistance of Alloy 22 in aerated 6 m NaCl + 0.9 m KNO<sub>3</sub> at 100°C

## CONCLUSIONS

- (1) Method 1 is not a recommended way of calculating Polarization Resistance since the fitting of dependent to independent variable is reversed. However, the difference in the results from Method 2 (proper fitting) is generally overshadowed by differences between specimen and specimen in the same testing conditions. The difference in results from Methods 1 and 2 will depend largely on the amount of noise in the data.
- (2) Method 2 provides the proper mathematical fitting of current vs. voltage data. Results are mathematically reproducible by a second operator. High noise in the experimental results may still yield high standard deviations and, sometimes, negative corrosion rates.
- (3) Method 3 gives values of polarization resistance that are practically undistinguishable from Method 2. Values of  $R_p$  using Method 3 cannot be precisely reproduced, even by the same operator.
- (4) In calculating polarization resistance (or corrosion rates) either Methods 2 or 3 may be used.

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