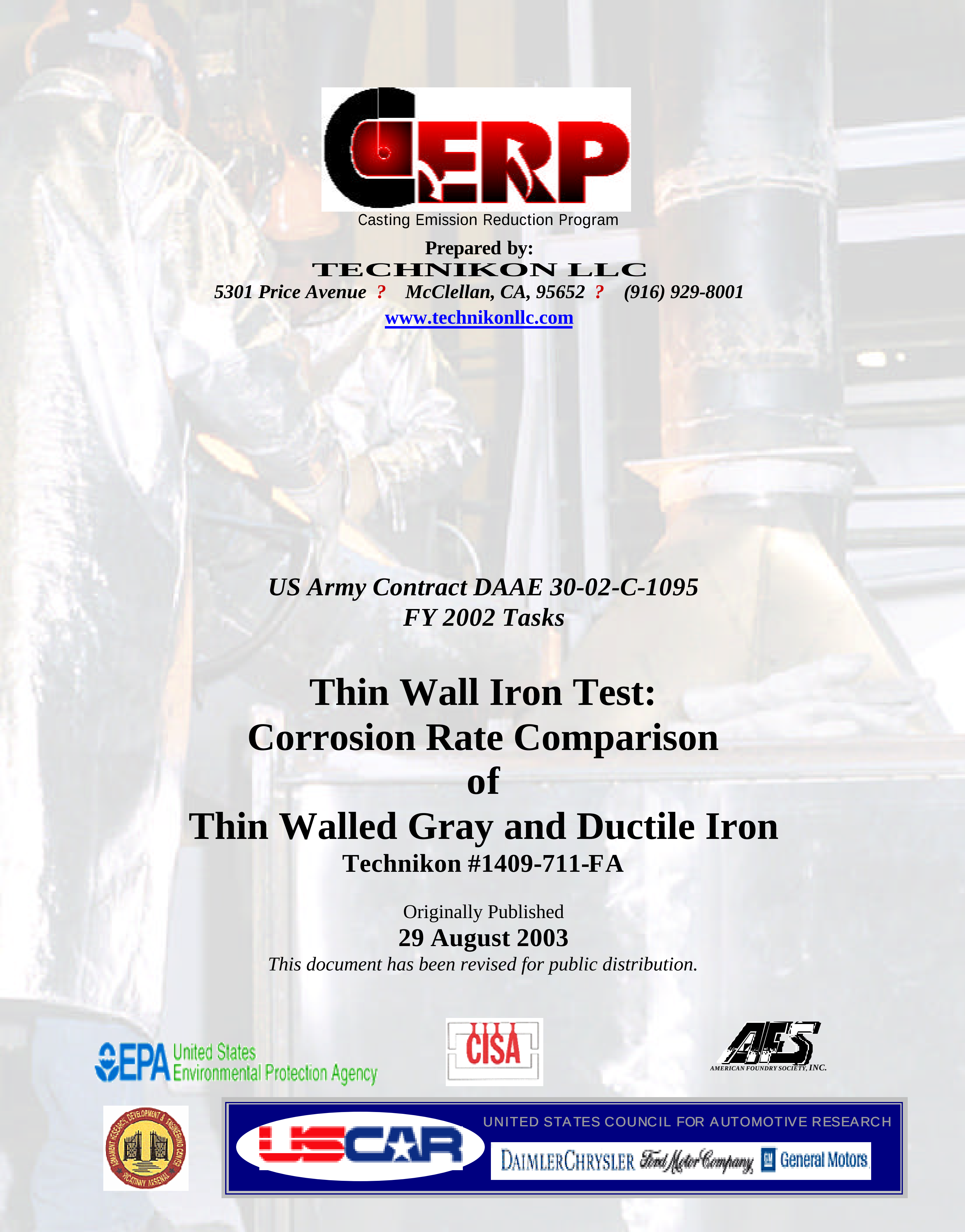

CERP

Casting Emission Reduction Program

Prepared by:

TECHNIKON LLC

5301 Price Avenue ? McClellan, CA, 95652 ? (916) 929-8001

www.technikonllc.com

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FY 2002 Tasks

Thin Wall Iron Test: Corrosion Rate Comparison of Thin Walled Gray and Ductile Iron

Technikon #1409-711-FA

Originally Published

29 August 2003

This document has been revised for public distribution.

EPA United States Environmental Protection Agency

CISA

AFS AMERICAN FOUNDRY SOCIETY, INC.

USCAR UNITED STATES COUNCIL FOR AUTOMOTIVE RESEARCH

DaimlerChrysler Ford Motor Company GM General Motors

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Thin Wall Iron Test: Corrosion Rate Comparison of Thin Walled Gray and Ductile Iron

1409-711 FA

This report has been reviewed for completeness and accuracy and approved for release by the following:

Process Engineering Manager:	*// Original Signed //* Steven Knight	Date
VP Measurement Technologies:	*// Original Signed //* Clifford Glowacki, CIH	Date
VP Operations:	*// Original Signed //* George Crandell	Date
President:	*// Original Signed //* William Walden	Date

The data contained in this report were developed to assess the relative corrosion characteristics of gray and ductile iron produced the Technikon casting facility. You may not obtain the same results in your facility. Data was not collected to assess casting quality, cost, or producibility.

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Executive Summary

This report contains the results of corrosion rate testing for thin wall castings made from two types of cast iron, class 30 gray iron and 60-45-12 ductile (aka nodular) iron. All the No-Bake molds and the gray iron castings were made at the Technikon, LLC production foundry. The ductile iron castings were poured at the Lodi Iron Works, Lodi, CA.

The test was divided into two (2) segments:

(1) Making of thin wall star castings in gray and ductile iron.
(2) Corrosion rate testing done at an outside lab (Materials Technology Associates).

The objectives of these tests were to determine the ability of making a thin wall star casting and to determine if the thin wall sections were more or less prone to corrosion than thicker walled castings of the same metallurgical composition. A pattern was made for a star casting that had progressively thinner fin sections on the drag pattern. The edge thickness varied from 2.5 to 4.0 mm. The balance of the casting had more typical 5.3 mm edges. Three No-Bake molds were poured in gray iron and three molds poured in ductile iron. These section sizes represent the practical limits of iron casting thinness as the edges were exhibited evidence of massive iron carbide (Fe_3C) formation. Segments were cut from the drag fins of these castings, excluding carbidic areas, ground smooth, and corrosion rate measured using a Potentiostat Test Cell.

The tables below summarize the results for each sample by type of metal and casting thickness.

Test FA Corrosion Rate in mils per year

Sample Number	Thickness of test Section in mm	Gray Iron Corrosion Rate Mils/year	Ductile Iron Corrosion Rate Mils/year
1	2.50	17.88	22.83
2	3.00	19.46	24.43
3	3.50	19.08	19.27
4	4.00	20.32	23.98

The conclusion drawn from the above data is that the corrosion rate of class 30 gray iron shows a slight significant relationship to section thickness in this range. The ductile iron corrosion rate showed no section size sensitivity.

It must be noted that the reference and product testing performed is not suitable for use as emission factors or for purposes other than evaluating the relative emission reductions associated with the use of alternative materials, equipment, or processes. The emissions measurements are unique to the specific castings produced, materials used, and testing methodology associated with these tests, and should not be used as the basis for estimating emissions from actual commercial foundry applications.

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1.0 Introduction

1.1 Background

Technikon LLC is a privately held contract research organization located in McClellan, California, a suburb of Sacramento. Technikon offers emissions research services to industrial and government clients specializing in the metal casting and mobile emissions areas. Technikon operates the Casting Emission Reduction Program (CERP). CERP is a cooperative initiative between the Department of Defense (US Army) and the United States Council for Automotive Research (USCAR). Its purpose is to evaluate alternative casting materials and processes that are designed to reduce air emissions and/or produce more efficient casting processes. Other technical partners directly supporting the project include: the American Foundry Society (AFS); the Casting Industry Suppliers Association (CISA); the US Environmental Protection Agency (US EPA); and the California Air Resources Board (CARB).

1.2 Technikon Objectives

The primary objective of Technikon is to evaluate materials, equipment, and processes used in the production of metal castings. Technikon's facility was designed to evaluate alternate materials and production processes designed to achieve significant air emission reductions, especially for the 1990 Clean Air Act Amendment. The facility has two principal testing arenas: a Pre-Production Foundry designed to measure airborne emissions from individually poured molds, and a Production Foundry designed to measure air emissions in a continuous full scale production process. Each of these testing arenas has been specially designed to facilitate the collection and evaluation of airborne emissions and associated process data.

The Production Foundry provides simultaneous detailed individual emission measurements using methods based on US EPA protocols for the melting, pouring, sand preparation, mold making, and core making processes. The core making area of the Production foundry contains three core blowers, a Georg Fischer for the preparation of automotive block cores, a Redford that is used for the production of step cores, and a second smaller Redford to produce dogbone tensile test specimens.

It must be noted that the results from the reference and product testing performed are not suitable for use as emission factors or for other purposes other than evaluating the relative emission reductions associated with the use of alternative materials, equipment, or manufacturing processes. The emissions measurements are unique to the specific castings produced, materials used, and testing methodology associated with these tests. These measurements should not be used as the basis for estimating emissions from actual commercial foundry applications.

1.3 Report Organization

This report has been designed to document the methodology and results of a specific test plan that was used to evaluate corrosion rate for thin wall castings. Section 2 of this report includes a summary of the methodologies used for data collection and analysis and data management. Specific data collected during this test are summarized in Section 3 of this report. Appendix B of this report includes the complete report from Materials Technology Associates Inc. Appendix C contains the mold making and pouring process data.

1.4 Specific Test Plan and Objectives

The Test Plan to make the molds and castings is included in Appendix A. The objectives of this testing was to determine if thinner wall castings would have a corrosion rate different from that of thicker walled castings of the same metallurgical character. Table 1-1 provides a summary of the test plan for the No-Bake mold making. The details of the approved test plans are included in Appendix A.

Table 1-1 Test Plan Summary

	Test FA
Type of Process Tested	Thin Walled Iron: Corrosion of Gray and Ductile Iron
Test Plan Number	1409-711-FA
Binder System	Phenolic Urethane No-Bake HA-International TECHNISET ® 20-665; 23-635; 17-727
Number of Molds	6: 3 for Gray iron, 3 for Ductile iron
Foundry Test Date	4/14/03 > 5/15/03
Process Parameters Measured	No-Bake mold weight, No-Bake binder content, Metal weight, Iron pour temperature, pour time, Metallurgical Data
Corrosion Measurement Method	Polarization Resistance using a Potentiostat with 3 % citric acid

2.0 Test Methodology

2.1 Description of Process and Testing Equipment

Figure 2-1 is a diagram of the No-Bake mold making process and testing equipment.

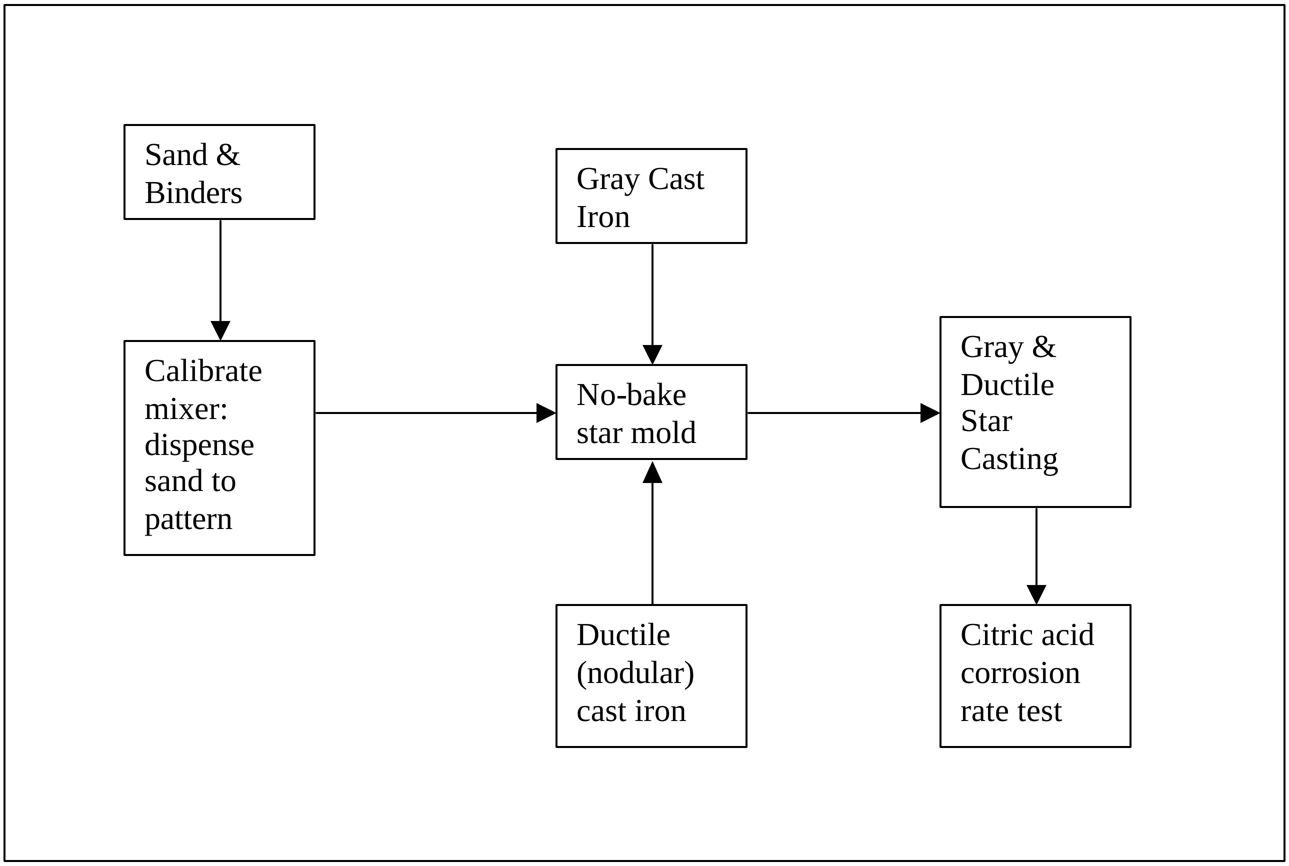


Figure 2-1 Mold Making and Testing Process

2.2 Description of Testing Program

The specific steps used in this sampling program are summarized below:

1. **<u>Test Plan Review and Approval:</u>** The proposed test plan was reviewed by the Technikon staff and the CERP Steering Committee, and approved.

2. **<u>Sand Preparation</u>:** Sands were mixed with quantities of designated binders in a Kloster paddle mixer. The sand was preheated or cooled as required to a standard temperature

range. The sand was mixed thoroughly and then dispensed at approximately 100 lbs/min into 12 x 16 x 6 inch cope and drag flasks containing a 1-on star matchplate pattern.


No-Bake Mold Line with Total Enclosure

3. **Mold Preparation:** No-Bake molding line. Mixed sand was dispensed into snap-flasks. Once the flasks were about one-half full, the vibration table was started to compact the mixed sand and it continued for an additional five (5) seconds after the flask was full. The excess sand was struck off and removed from the test enclosure.

4. **Where new core materials are being evaluated, initial core emissions baseline data are gathered by placing five step-block cores under anProcess Parameter Measurements:** Table 2-1 lists the process parameters that are monitored during each test. The analytical equipment and methods used are also listed.

Table 2-1 Process Parameters Measured

Parameter	Analytical Equipment and Methods
Binder Weight (mixing)	Mettler PJ8000 Digital Scale (Gravimetric)
Sand Weight (mixing)	OHAUS 110# digital platform scale
Sand Temperature (mixing)	Stem type dial thermometer
Cycle Time	Digital elapsed time clocks
Mold Weight	Cardinal 748 Digital Platform Scale

5. **Casting Process:** A single one-on Star pattern was built for this test that had variable fin thickness in the drag pattern. These thicknesses were 2.5 millimeters, 3.0 millimeters, 3.5 millimeters and 4 millimeters measured along the free edge. The standard fin thickness in the cope pattern is 5.3 millimeters. Six molds were prepared of which three molds were poured with gray iron and three molds poured with ductile iron. The castings were lightly cleaned with a wire brush.

Figure 2-2a Thin walled Star Casting with Gating Attached.

Figure 2-2b Single Star Drag Pattern

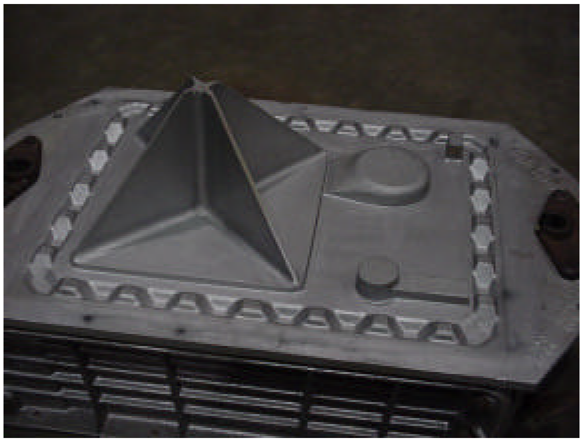
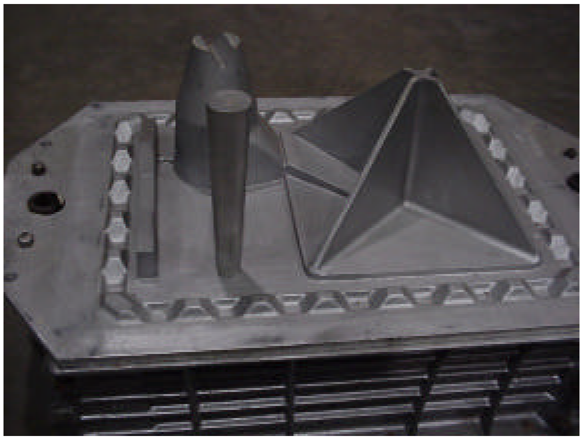


Figure 2-2c Single Star Cope Pattern



6. **Report Preparation and Review:** The Preliminary Draft Report is reviewed by the Manager, Process Engineering, and the Emissions Team to ensure its completeness, consistency with the test plan, and adherence to the prescribed QA/QC procedures. Appropriate observations, conclusions and recommendations are added to the report to produce a Draft Report. The Draft Report is reviewed by the Vice President-Measurement Technologies and the Vice President-Operations. Comments are incorporated into a Final Report prior to final signature approval and distribution.

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3.0 Test Results

Gray Cast Iron

The gray cast iron samples had very similar surface characteristics, and a good finish on each section was obtained through milling. Table 3-1 shows the corrosion rates for the 4 gray iron samples in mils per year. Appendix B figures 1 through 4 contains the polarization resistance plots obtained from the potentiostat. The trend line represents the polar resistance which is used to calculate the corrosion rate.

Table 3-1 Gray Cast Iron Corrosion Rates in Mils per Year

Sample Thickness mm	Polarization Resistance Ohms	Corrosion Rate (mils/yr)
2.50	81.31	17.88
3.00	74.69	19.46
3.50	76.17	19.08
4.00	71.63	20.32

Nodular Cast Iron

The nodular cast iron samples had much more surface occlusions than the gray cast iron samples. These were effectively removed with surface milling. Table 3-2 shows the corrosion rates for the four nodular cast iron samples. Appendix B figures 5 through 8 are the polarization resistance plots obtained from the potentiostat.

Table 3-2 Nodular Cast Iron Corrosion Rates in Mils per Year

Sample Thickness mm	Polarization resistance Ohms	Corrosion Rate (mils/yr)
2.50	63.67	22.83
3.00	59.50	24.43
3.50	75.44	19.27
4.00	60.62	23.98

Figure 3-1 Corrosion Rate for Gray Iron: Data from Table 3-1

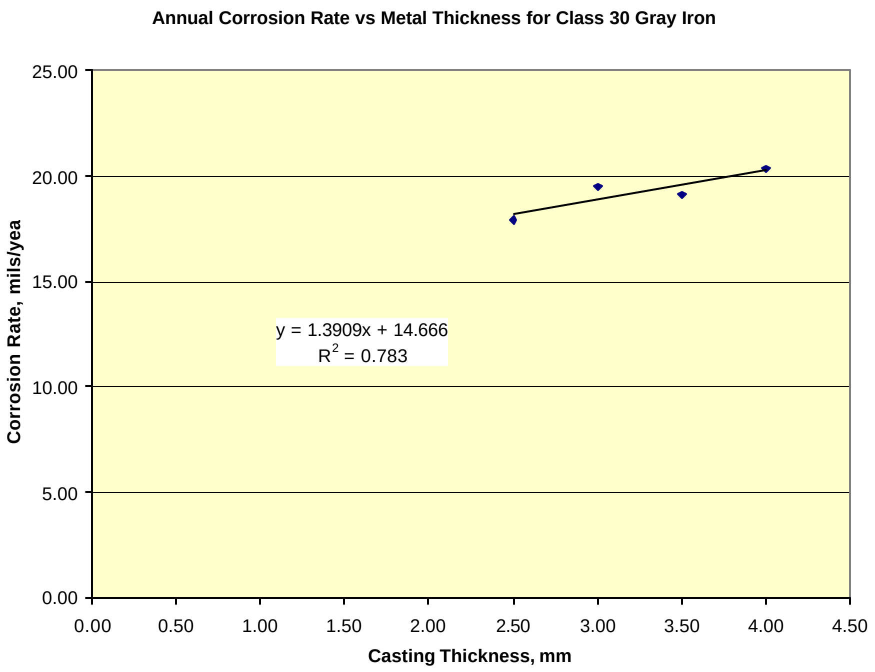
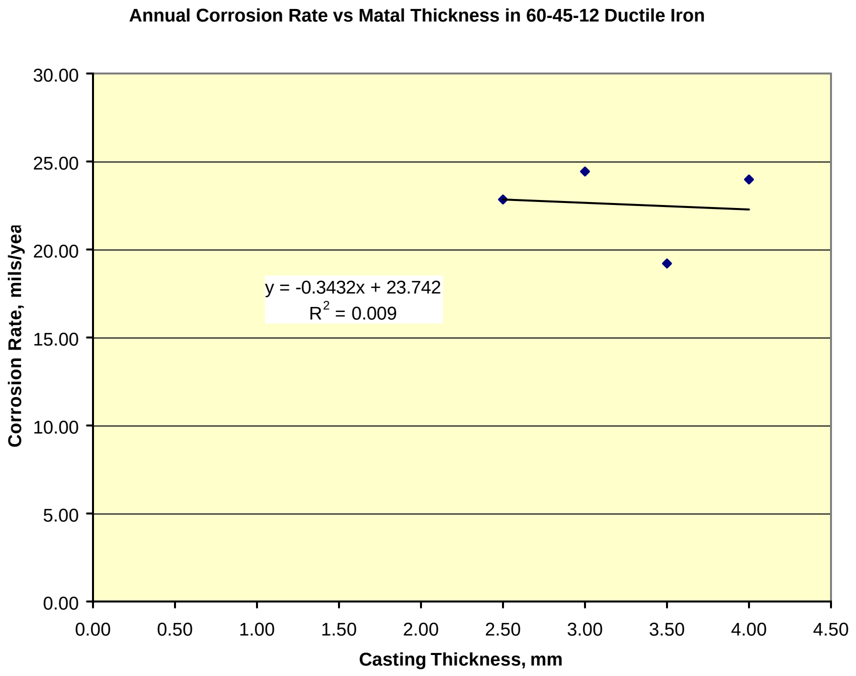


Figure 3-2 Corrosion Rate for Ductile Iron: Data from Table 3-2



4.0 Discussion of Results

Obtaining a representative real world corrosion rate is not a perfect science because the rate is dependent on the corrosive environment to which the materials are subjected as well as the local variation in the material's chemistry and processing. The method chosen to evaluate the corrosion rate has a good industrial reputation for being able to yield repetitive results under the same conditions.

A three (3) percent citric acid solution was chosen as the corroding medium because of its common use in the chemical cleaning of steel. Steel shares a common base metal of iron with cast iron. Cast iron is however a substantially different material from steel because of the excess carbon as a second phase not present in steel. The carbon content for the gray iron is in the 3.2-3.4 % range and for the ductile iron is in the 3.6-4.0 percent range. Additionally gray iron contains a more or less continuous graphitic matrix whereas in the ductile iron the graphite is in discrete nodules. The result is that the two metals have different properties including the electrical properties measured as part of this test. The reader therefore must be cautious when comparing the corrosion characteristics derived from electrical measurements of the two materials.

The four samples representative of the two iron types were each cut from a single casting of the respective metal types in order to have chemical and processing consistency. One side of each sample was milled parallel to the surface sufficient to only remove surface irregularities. The backside was milled parallel to the front side at a constant residual thickness of 0.125 +/-0.002 inches. The only variable within a metal group should then be the as-cast geometric differences and the metallurgical consequences of that geometry.

The slight progression of corrosion rates for the gray cast iron samples indicates that the variation in sample thickness has a small effect on the corrosion rate. The statistical confidence is supportive given the small sample size.

The variation in the corrosion rate of the nodular cast iron samples does not appear to be caused by the difference in thickness of the sections as their corrosion rates are not proportional. The different corrosion rates among the nodular iron samples are more likely caused by the internal porosity of the sections and inclusion of non-conductive micro-constituents. The statistical confidence level supports the indeterminacy of relationship to the chosen parameter, casting thickness. Additional experimentation over a wider variation of section thickness might be revealing.

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APPENDIX A APPROVED TEST PLAN AND SAMPLE PLAN FOR TEST FA

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TECHNIKON TEST PLAN

- **CONTRACT NUMBER: 1409 TASK NUMBER: 7.1.1 Series: FA**
- **WORK ORDER NUMBER: 1175**
- **SAMPLE EVENTS: 001 thru 018**
- **SITE: __X__PRE-PRODUCTION ___ FOUNDRY**
- **TEST TYPE:** Corrosion study of grey and ductile iron castings with variable wall thickness.
- **METAL TYPE:** 80-55-06 ductile iron and class 30 grey iron
- **MOLD TYPE**: No bake sand mold made with HA International 7211 Resin, 7706 Co-reactant, and 17-727 Activator
- **NUMBER OF MOLDS: 6**
- **CORE TYPE: None**
- **TEST DATE: START: 3 Apr 2003**
  FINISHED: 20 Apr 2003

TEST OBJECTIVES: Cast commercial grade star castings in grey and ductile iron and subject them to a standard cleaning and salt corrosion tests.

VARIABLES : Casting thickness will be varied in the range of 2.5mm-5.3 mm plus draft.Metal will be poured at 2650 +/- 10 ^{o}F.
The nobake mold binder will be 1.3 % total binder (BOS) in 55/45 ratio of part I/partII and the activator is 10% of part 1.

BRIEF OVERVIEW: No emission testing is associated with this test. Good quality castings free of surface casting defects and internal porosity are important. A no-bake mold is being used to maintain better dimensional control and improve casting surface better than would be possible in a green sand mold.

SPECIAL CONDITIONS: All molds will be 12 x 16 x 6/6 inch with a 4 inch pouring basin on top.

Process Engineering Manager **(Technikon)**	**Date**
V.P. Measurement Technology **(Technikon)**	**Date**
V.P. Operations **(Technikon)**	**Date**
Test Design Committee Representative	**Date**
Emission Committee Representative	**Date**

APPENDIX B DETAILED REPORT FOR TEST FA

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Materials Technology Associates Inc.

1857 Krpan Drive, Roseville, CA 95747 Phone 916 772-8617 Fax 916 772-8615

CUSTOMER: George Crandell
cc Steven Knight

CUSTOMER PO NO: 0316103

COMPANY: Technikon LLC

REPORT DATE: 8-14-2003

SUBJECT: **Corrosion Rate Measurements of Cast Iron Samples of Varying Thickness.**

Abstract

Four samples of gray cast iron and four samples of nodular cast iron were received in order to determine if there is a correlation between the thickness of the material and its corrosion rate. The samples varied from 2.50mm to 4.00 mm in steps of .50 mm, and their corrosion rates were measured by using polarization resistance with a potentiostat. It was concluded that the corrosion rate does not depend on the thickness of the sample.

Introduction

Eight samples of cast iron were received in order to determine if there was a correlation between the thickness of the material and its corrosion rate. Polarization resistance was used to determine the corrosion rates for the samples because it is a very precise and well developed method. The theoretical basis for this method is outlined in the appendix. The tests were performed in a 3% citric acid solution, which was chosen because it is a mild organic acid that is commonly used to clean steel.

Experimental procedure

Both the gray cast iron samples and the nodular cast iron samples were numbered 1 through 4, with 1 corresponding to the smallest edge thickness and 4 corresponding to the largest edge thickness. Sections were cut out of each sample that were large enough to cover the 9 cm^2 hole in the bottom of the potentiostat, which created a uniformly sized electrode. Care was taken to use sections from the middle of the samples as the edges had a region that was much harder than the bulk of the material.

Each sample was then connected to the potentiostat and polarization resistance measurements were done. A linear curve fit through the plots obtained allowed for the corrosion rate for each sample to be calculated in mils per year (mpy), where 1 mil is equivalent to 0.001 inch. The two material constants needed to calculate the corrosion rate are the density and the equivalent weight, and these parameters were taken as 7.17 g/cm^3 and 27.92 gm/valence electron respectively for both materials.

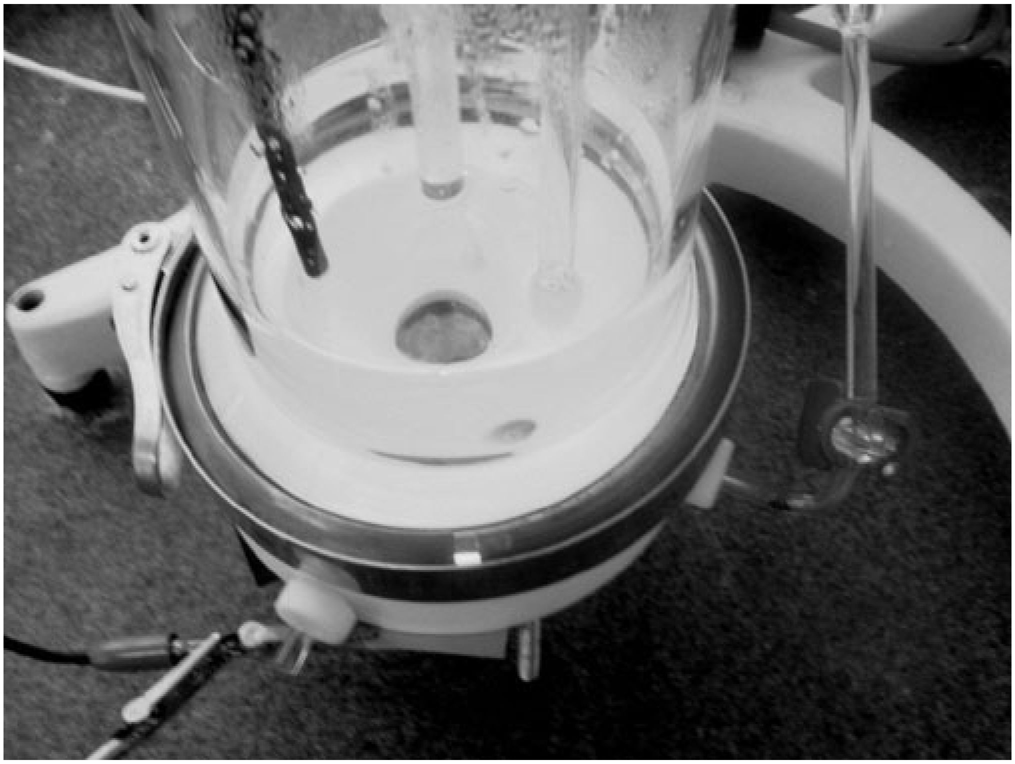

Figure 1:
Potentiostat Test Cell

Shows the potentiostat cell used for this test. The sample is pressed against the o-ring at the bottom of the cell, and this circular area is what is exposed to the solution. The graphite rod to the left is the counter electrode that is used to raise the potential of the sample, and the glass rod on the right contains a reference electrode to measure the potential of the sample.

Results

Gray Cast Iron

The gray cast iron samples had very similar surface characteristics, and a good finish on each section was obtained through polishing. Table 1 shows the corrosion rate data for the four gray cast iron samples in mils per year, and figure 2 shows the dependence of the corrosion rate on sample thickness. Figures 4 through 7 are the plots obtained from the potentiostat.

Sample	Sample Thickness (mm)	Corrosion Rate (mpy)	Corrosion Current I_{corr} (µA)	Resting Potential E_{corr} (mV)	Polarization Resistance Rp (Ω)	Experimental Temperature (°C)
1	2.5	17.88	320.8	-727.0	81.31	22.2
2	3.0	19.46	349.3	-721.5	74.69	22.2
3	3.5	19.08	342.5	-727.5	76.17	22.3
4	4.0	20.32	364.7	-714.4	71.53	22.4

Table 1:
Gray Cast Iron Corrosion Rates

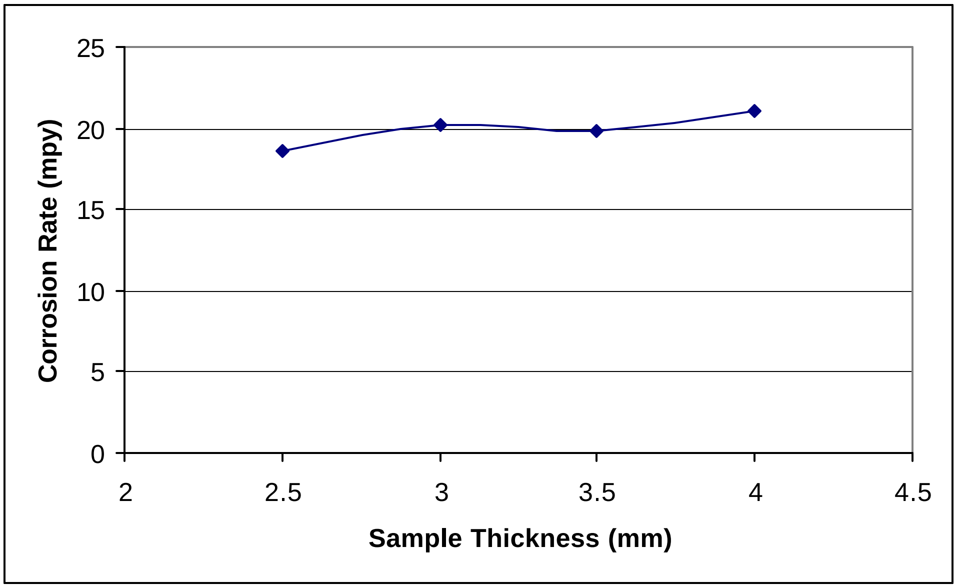

Figure 2:
Gray Cast Iron Corrosion Rate vs. Material Thickness

Nodular Cast Iron

Excellent surface finishes were obtained on all of the nodular cast iron samples except for sample number 3, which had slight surface porosity. Table 2 shows the corrosion rate data for the four nodular cast iron samples, and figure 3 shows the dependence of corrosion rate on material thickness. Figures 8 through 11 are the plots obtained from the potentiostat.

Sample	Sample Thickness (mm)	Corrosion rate (mpy)	Corrosion Current i_{corr} (μA)	Resting Potential E_{corr} (mV)	Polarization Resistance Rp (Ω)	Experimental Temperature (°C)
1	2.5	22.83	409.2	-713.9	63.67	21.8
2	3.0	24.43	437.9	-696.5	59.50	21.9
3	3.5	19.27	345.4	-704.1	75.44	21.9
4	4.0	23.98	429.8	-687.6	60.62	21.9

Table 2:
Nodular Cast Iron Corrosion Rates

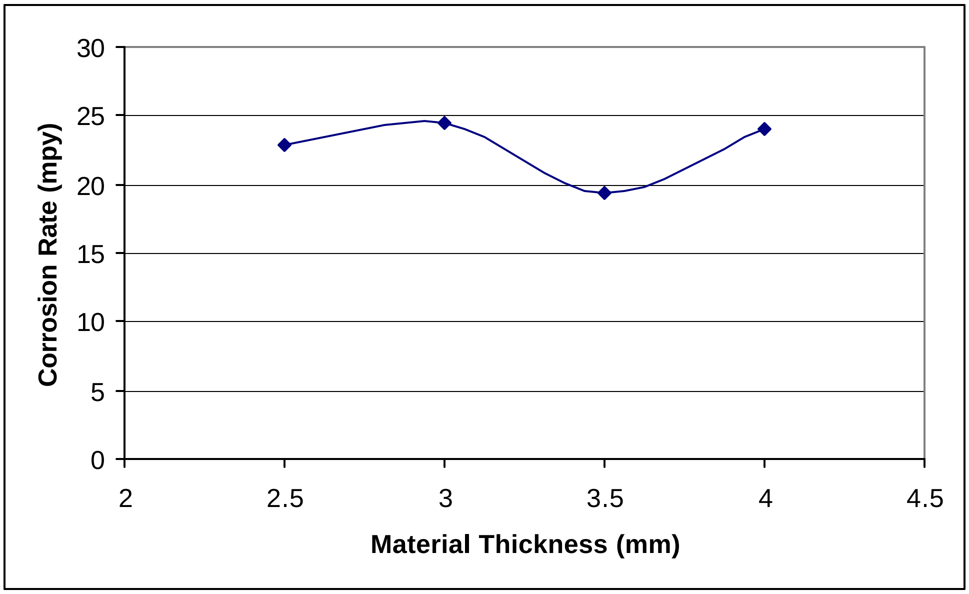

Figure 3:
Nodular Cast Iron Corrosion Rate vs. Material Thickness

Conclusion

The close grouping of the corrosion rates for the cast iron samples indicates that the variation in sample thickness has little significant effect on the corrosion rate.

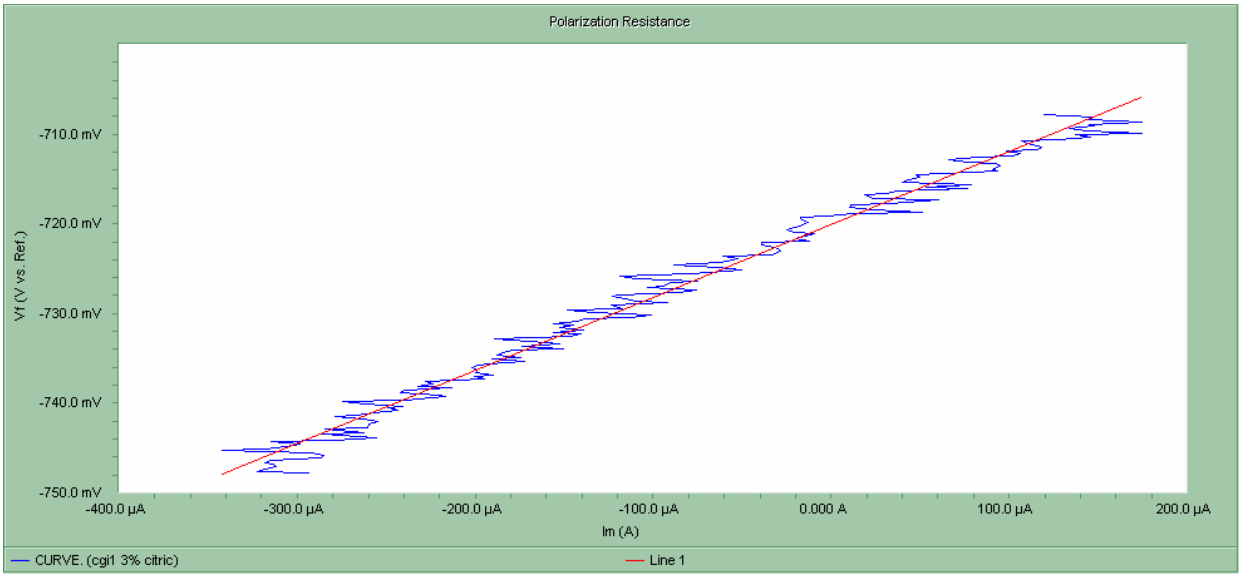

Figure 4:
Grey Cast Iron Sample 1 - Corrosion Rate: 17.88 mpy

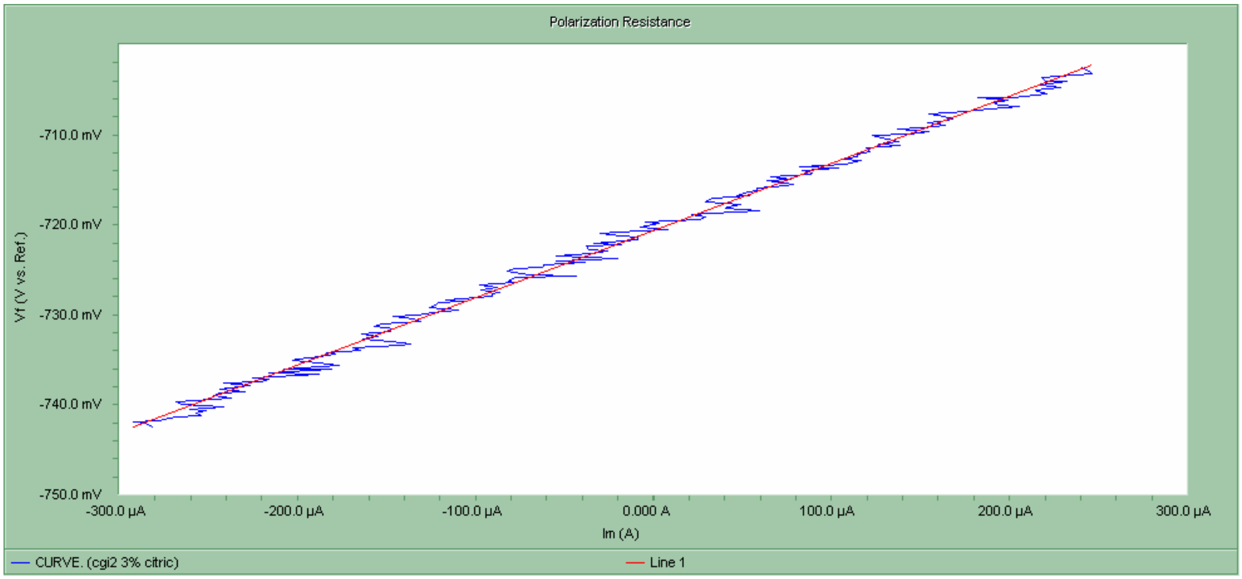

Figure 5:
Grey Cast Iron Sample 2 - Corrosion Rate: 19.46 mpy

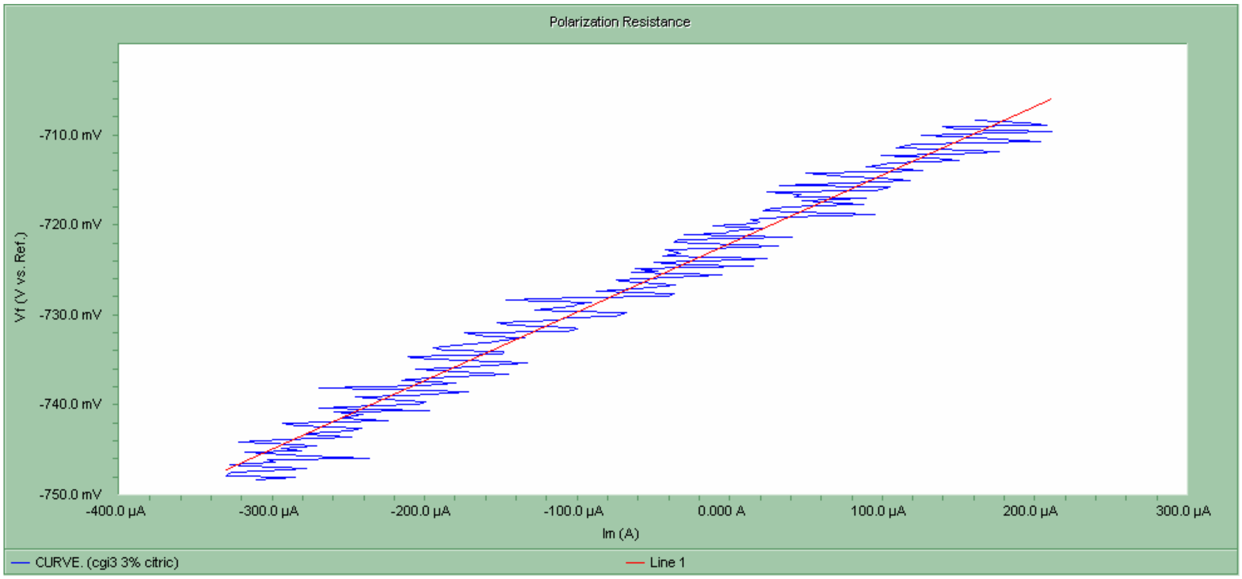

Figure 6:
Grey Cast Iron Sample 3 - Corrosion Rate: 19.08 mpy

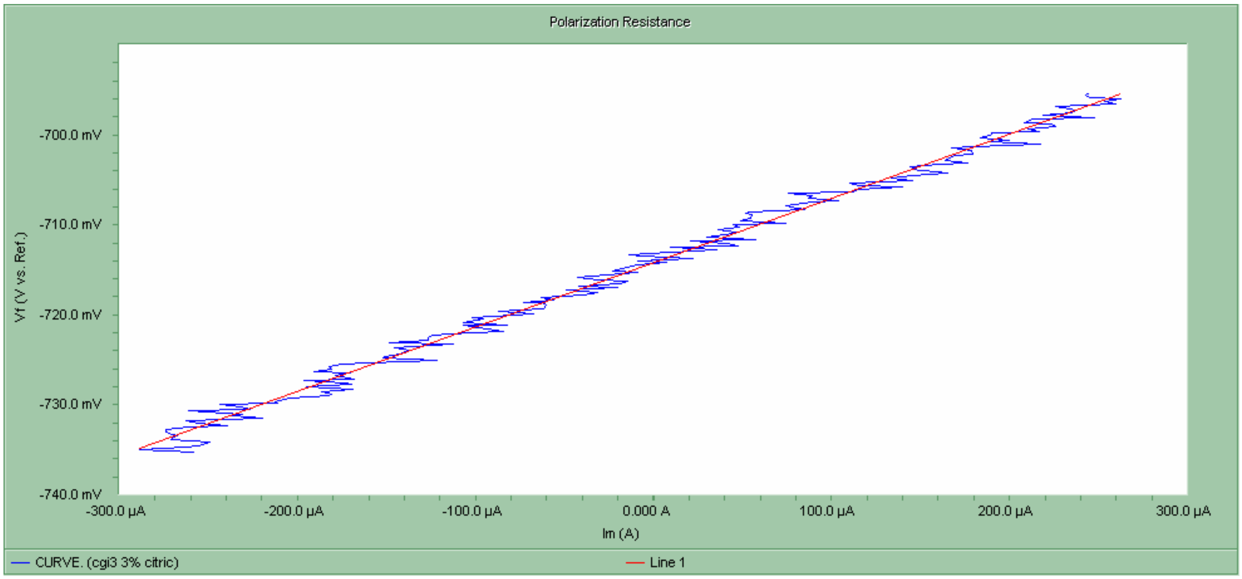

Figure 7:
Grey Cast Iron Sample 4 - Corrosion Rate: 20.32 mpy

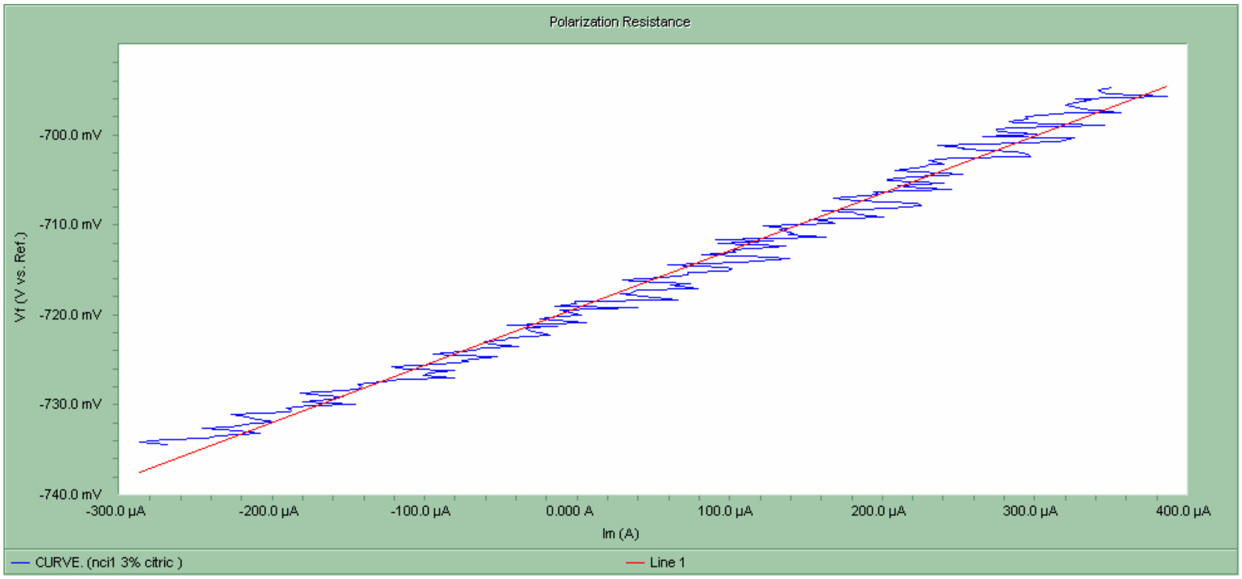

Figure 8:
Nodular Cast Iron Sample 1 - Corrosion Rate: 22.83 mpy

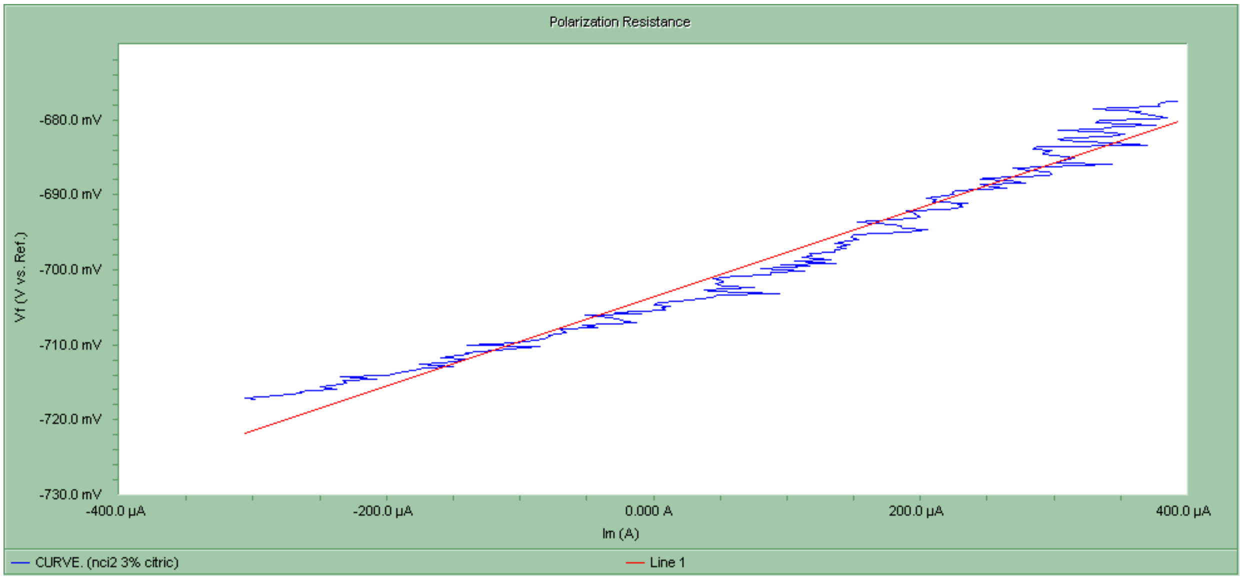

Figure 9:
Nodular Cast Iron Sample 2 - Corrosion Rate: 24.43 mpy

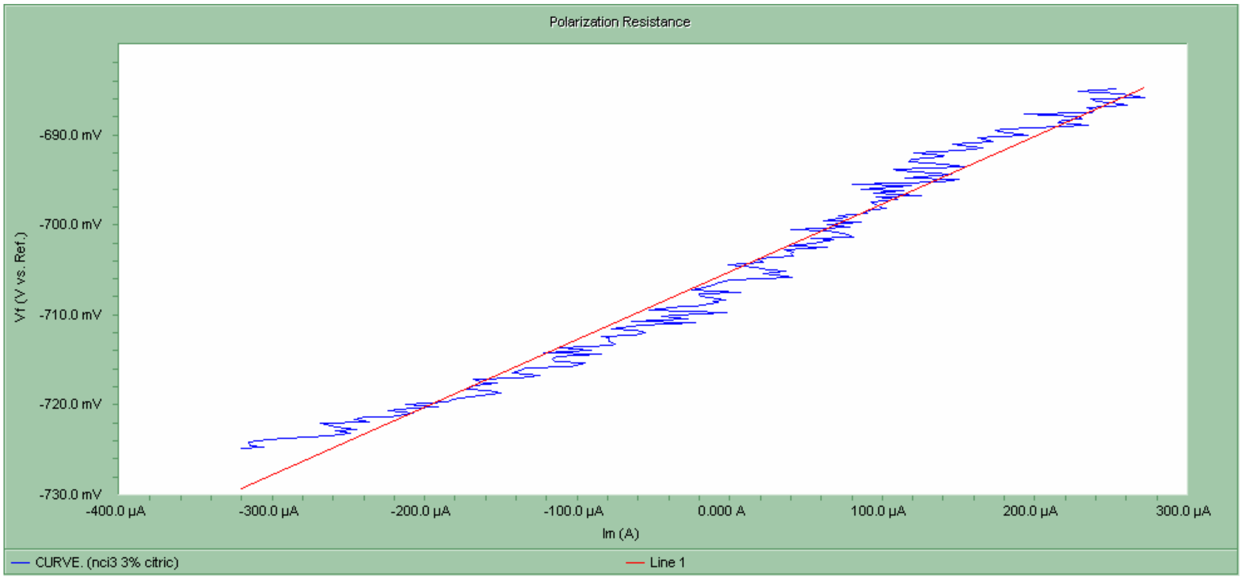

Figure 10:

Nodular Cast Iron Sample 3 - Corrosion Rate: 19.27 mpy

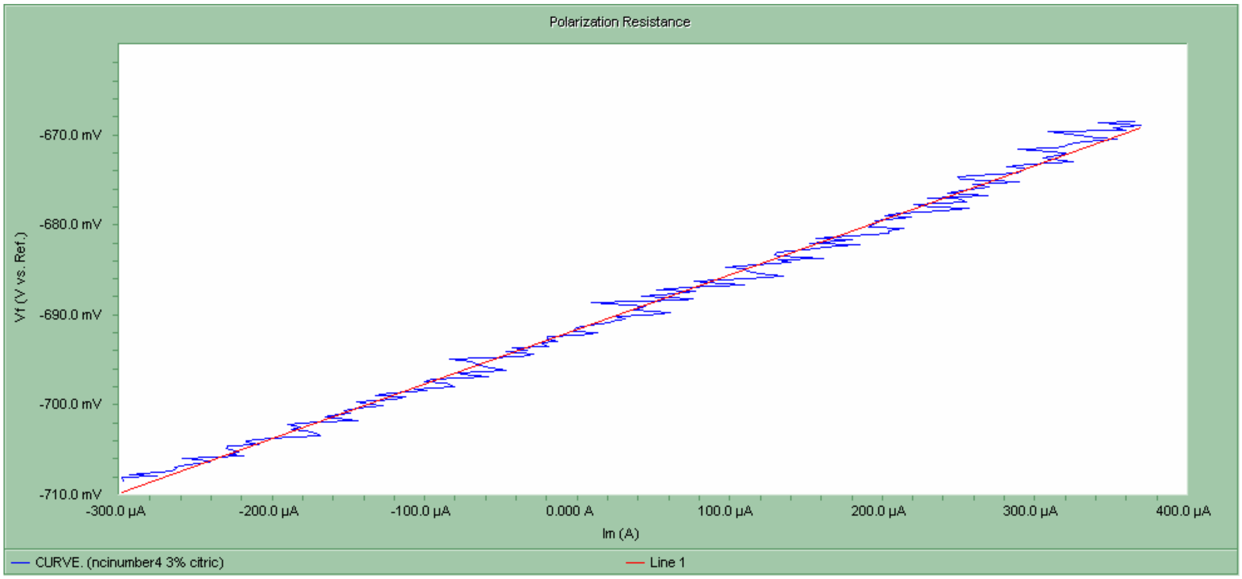

Figure 11:
Nodular Cast Iron Sample 4 - Corrosion Rate: 23.98 mpy

Appendix
(Explanation of Polarization Resistance)

The polarization resistance (R_P) is a parameter that is obtained with a potentiostat by polarizing a sample close to its resting potential (E_{corr}). This is done by varying potential and measuring current, which in the neighborhood of E_{corr} is a linear relationship. A plot is then produced such as the one shown in figure 12. Since the plot is linear, Ohm's Law allows us to assign a resistance value to this slope, which is the parameter R_P as shown in equation 1.

$DE/DI = R_P$ **Eqn. 1**

Once the polarization resistance is known, the corrosion current can be determined using equations 2 -5.

$R_P = B/i_{corr}$ **Eqn. 2**

$B = b_A b_C/2.3(b_A + b_C)$ **Eqn. 3**

The parameters b_A and b_C are typically assumed to be 0.12 volts, which represent the average of all corrosion systems. This reduces equation 2 to the form seen in equation 4 and 5.

R_P (ohms) = 0.026V/i_{corr} (amperes) **Eqn. 4**

i_{corr} (µA) = 26086.9/ Rp (ohms) **Eqn. 5**

The size of the cathode is determined by how much of the sample is exposed to the solution in the potentiostat, which for the case of our potentiostat is a 9 cm^2 circle. The corrosion rate can then be calculated in microns per year using equations 6-8, where i_{corr} is in µA, EW is the equivalent weight of the material in gm/valence electron (atomic weight / no. of valence electrons), ? is the metal density in gm/cm^3, and A is the area of the sample exposed to the electrolyte in square centimeters. The number 96487 is the ratio of Avogadro's number 6.022×10^{23} (the number of atoms in 1 gm-mole) / 6.241×10^{18} (the number of electrons the sum of whose charge is 1 coulomb). The number 31556930 is the number of seconds in one year. The number 100 resolves the scale so that microamperes can be used in place of amperes for i_{corr} and square centimeters can be used in place of square meters for the electrolyte area and have the results expressed as µm/yr.

Corrosion Rate (mm/y) = i_{corr}*EW*31556930/ (?*96487*A*100) **Eqn. 6**

Corrosion Rate (mm/y) = 3.2706*i_{corr}*EW/ (?*A) **Eqn. 7**

Since one mil per year is equal to 25 microns per year, the corrosion rate can then be calculated using equation 6.

Corrosion Rate (mpy) = Corrosion Rate (mm/y)/25.4 **Eqn. 8**

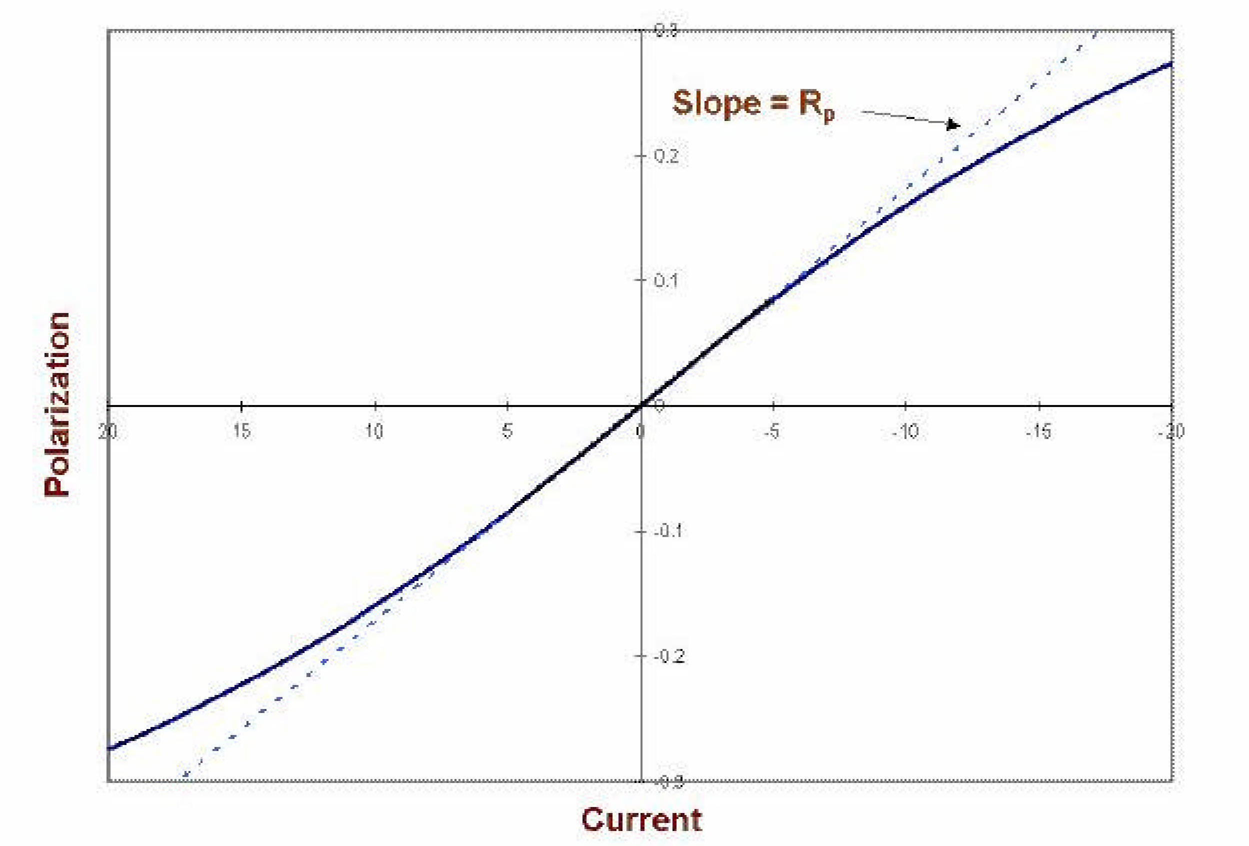

Figure 12:
Plot of polarization voltage vs. measured current

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APPENDIX C DETAILED PROCESS FOR TEST FA

Process Parameter	Gray Cast Iron	Ductile Cast Iron
Mean Mold weight, Lbs	114	114
Mean Binder Weight, Lbs	1.48	1.48
Mean Casting weight	31.0	30.8
Pour Time, Seconds	12	13
Pour Temperature, F	2648	2600-2650 (Note)

Note: Lodi Iron Works Ductile Iron pouring specification