



CORROSION PROTECTION OF DUCTILE IRON PIPE

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From the desk of...

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ABSTRACT

The results of a two-year study of corrosion and corrosion protection characteristics of ductile iron pipe are presented. Included are field and laboratory evaluations related to short term and long term polarization rates under varying conditions; corrosion rate reduction and corresponding cathodic current criterion; and the corrosion protection benefits of the traditional, standard asphaltic shop coating. This information was then analyzed in conjunction with an extensive database from 1379 physical inspections of buried iron water lines. The result of the study is a risk based corrosion protection design strategy for buried ductile iron pipelines.

Key Words: Ductile Iron, Ductile Iron Pipe, Corrosion of Ductile Iron Pipe, Coating of Ductile Iron Pipe, Cathodic Protection of Ductile Iron Pipe, Corrosion Protection Design Decision Model

1. INTRODUCTION

Not all soil environments are corrosive to ductile iron pipe. Although corrosion may be occurring, the rate of corrosion may be acceptable for the service life of the pipe. Properly designed and installed cast iron pipe systems in moderately corrosive soils have demonstrated performance of more than 100 years of service. Over 50 years of test results, field inspections and in-service operations indicate that similar results are expected for ductile iron pipe.

When soil tests and performance history indicate that conditions are corrosive to ductile iron pipe (DIP), positive corrosion protection is warranted. Corrosion protection scenarios for DIP typically include polyethylene encasement, stray current control and cathodic protection.

This two-year research effort was undertaken in cooperation with the Ductile Iron Pipe Research Association (DIPRA) to evaluate the circumstances and field conditions that warrant the appropriate level of corrosion protection to achieve a useful life of 75 to 100 years. It is recognized that there are differences between ductile iron and steel pipe materials and protective coating systems, and that there are differences between these materials with respect to pipeline service and operating conditions.

The research effort encompassed the following:

- Laboratory Studies of corrosion rates and polarization characteristics.
- Field Measurements of corrosion rates on lengths of production pipe.
- Direct Examination of operating pipelines.
- Design Decision Model development for defining corrosion protection requirements.

Over the last several years there has been much controversy in industry over corrosion control strategies for ductile iron pipelines used in the water and wastewater industries. Much of this stems from the application of corrosion control standards and guidelines (e.g. NACE RP0169) that were developed primarily to address regulated oil and gas energy pipelines where complete cathodic protection is mandated and corrosion is not acceptable. Typically for ductile iron pipelines, some corrosion is tolerable and these pipelines are typically not regulated.

The results of this research demonstrate that high quality dielectric coatings are not necessary or practical for corrosion control of DIP. The evaluation concludes that when the use of a cathodic current is deemed appropriate, the levels of current to provide a practical service life extension are notably less than the highly conservative industry norms established for regulated pipelines. Acknowledging both of these facts is fundamental for prudent corrosion control engineering for DIP and can result in a considerable cost savings in corrosion control practices.

2. CORROSION PROTECTION RESEARCH

Research pertaining to corrosion and corrosion protection of ductile iron pipe included various laboratory and field tests:

- Aqueous Solution Studies
- Soils Research
- Cathodic Polarization
- Electrical Resistance of Standard Asphaltic Shop Coat

Aqueous Solution Studies

The first series of laboratory tests consisted of electrochemical and electrical tests on 100 ductile iron pipe samples in five aqueous solutions of different electrical resistivity. Aqueous solutions, rather than soil, were used for the initial evaluation to establish some basic pipe characteristics that might be distorted if investigated using typical heterogeneous soils.

The ductile iron pipe samples were tested with five coating conditions:

- “Bare” – no asphaltic shop coat, standard production annealing oxide intact.
- “New Thin” – normal thickness (average 8.8 mils) annealing oxide/asphaltic shop coating without exposure to ultraviolet light (UV).
- “New Thick” – above normal thickness (average 14.2 mils) annealing oxide/asphaltic shop coating without exposure to UV.
- “Old Thin” – normal thickness (average 8.5 mils) annealing oxide/asphaltic shop coating with approximately one year UV exposure.
- “Old Thick” – above normal thickness (9.9 mils) annealing oxide/asphaltic shop coating with approximately one year UV exposure.

The thickness measurements reflect the total coating system, which consists of both the asphaltic shop coat and the annealing oxide. The thickness measurements were made with a standard magnetic pull-off

gauge. Note that the rough, peen surface of DIP makes coating thickness measurements difficult and inherently not particularly accurate.

Five aqueous solutions of different resistivities were chosen to reflect extremely low to moderate soil resistivity conditions. For the initial tests, the use of homogeneous, aqueous solutions provided for control of the resistivity of the environment and resulting reproducibility of test results among sample sets. Each of the five solutions was prepared by mixing with seawater or deionized water to achieve the desired resistivity (see Table 1).

Table 1: Test Solution Resistivity

TEST SOLUTION	Ratio (by volume)	Resistivity (ohm-cm)
Natural Seawater	--	25
Fresh (tap) water adjusted with Seawater	28:1	500
Fresh (tap) water adjusted with Seawater	68:1	1,000
Fresh (tap) water adjusted with Seawater	950:1	3,000
De-ionized water adjusted with Fresh (tap) water	21:10	10,000

Electrochemical techniques were used to evaluate the corrosion characteristics of DIP in each of the five electrolytes. Tafel ($E \log I$) behavior was analyzed to define general corrosion rates, cathodic current requirements, and relative currents for corrosion rate reduction (i.e., life extension). The E -log I scans (140 total) were performed by applying a known current to obtain a voltage shift from E_{corr} (the free corrosion potential). Prior to running the E -log I scan, E_{corr} was monitored until a stable potential was reached. These scans were run from below to above E_{corr} (i.e. from the cathodic to anodic regions) using a Gamry™ PC4 computer controlled potentiostat .

The potentiodynamic E -log I scans were generated on the bare and coated samples of DIP at a scan rate of 0.17 millivolt per second. This production scan rate was selected after initial measurements showed there was some variance in the data using rates between 0.17 and 0.5 millivolt per second. Rates slower than 0.17 millivolt per second yielded no appreciable change. The slower the scan rate, the better the data reflects corrosion tendencies and corrosion protection.

The potential range selected for the E -log I scans started from an absolute value of -0.850 volt (cathodic) to +0.250 volt (anodic) above the open circuit potential (E_{corr}). All potential measurements were made relative to a copper/copper sulfate electrode (CSE) and were IR drop corrected. The potential range was chosen to capture both the anodic and the cathodic reactions of the DIP in each electrolyte and to provide protection data to the -0.850 volt level. Evaluation of these data was used to determine the relative reduction in corrosion current for various levels of life extension.

Figure 1 is a representative E -log I scan. The corrosion rate was determined from the plot of potential versus the log of current density. Using Tafel analysis, the linear (straight) portions of the anodic and cathodic legs of the voltage/current relationship are extended, with the point of intersection indicating the corrosion current under a freely corroding condition. Figure 2 shows a schematic of this graphical analysis.

Using this graphical analysis, the general corrosion rate (in mils per year) for the DIP samples was calculated from the corrosion current as shown below:

$$CR = K * \frac{i_{corr} * E.W.}{\rho}$$

where,

- CR = corrosion rate in mils per year,
- K = is a constant depending on units (0.129 for mpy),
- i_{corr} = corrosion current density in $\mu\text{A}/\text{cm}^2$,
- E.W. = equivalent weight in grams, 27.89 g for ductile iron, and
- ρ = density of $7.06 \text{ g}/\text{cm}^3$ for ductile iron

This analysis provides the instantaneous general corrosion rate of a single sample at the time of measurement, assuming all of the metal substrate is exposed to the test environment. Protective current requirements were calculated based on i_{corr} at the points of reduced corrosion rate.

Referencing Figure 3, as a cathodic current is applied, there is a corresponding reduction in the corrosion current and therefore, corrosion rate. To determine the service life extension current characteristics for DIP, the potentials (e.g. E_{pol} and E_{pol}') were determined graphically from the cathodic leg of the Tafel relationship over a range of corrosion reducing currents (e.g. i' and i''). This “IR compensated” potential is that necessary to reduce the corrosion rate of the test sample. The polarization of the test sample at a given corrosion reducing current is calculated as the difference between potential at that current (e.g. E_{pol}') and the corrosion potential (E_{corr}).

The concept of using a (reduced) cathodic current to extend service life, as determined by Tafel characteristics, is not new. Published literature on the use of electrochemical (polarization) techniques to estimate corrosion reduction levels includes that by D.A. Jones in 1972.

Corrosion protection current analysis was performed on both bare and coated test samples. This analysis considered the general corrosion rate of test samples and the cathodic current requirements to achieve relative corrosion rate reductions. The testing demonstrates that standard, asphaltic shop coating does provide some corrosion protection. The corrosion rates are lower on coated samples, and thus requires less current for corrosion protection compared to the bare DIP.

Soils Research

Following the testing in aqueous solutions, five soils of various origins were collected for similar long-term polarization testing in the laboratory and in the field. The sites selected were chosen to represent a range of conditions where life extension corrosion protection might be employed, i.e. conditions where pipe with standard asphaltic shop coat would not afford the desired pipe life. Data from the following Table 2 summarizes the test locations and soil corrosivity.

Table 2: Test Soil Corrosivity

Test Soil	Soil Type & Color	Resistivity (ohm-cm)	Moisture Content (%)	PH	Chlorides (ppm)	Sulfides (ppm)
Spanish Fork, Utah (1)	Silty Clay – Light Gray	68	26	8.2	5896	0
Everglades, Florida (1)	Organic Loam – Dark Gray	124	136	7.7	4402	Positive
Hughes, Arkansas (1)	Clay – Light Yellow Gray	600	47	5.3	2	0
Raceland, Louisiana (1)	Clay – Light Yellow Gray	1280	39	8.1	4	0
Orange, California (2)	Sandy Clay Loam – Light Brown	1800	12	7.7	12	0

(1) Research/test site

(2) Pipe excavation/inspection site

Use of representative soil samples for laboratory testing allowed for comparison to data collected in the field on pipe samples installed in the same environments. At each of four test/research sites (Spanish Fork, Everglades, Hughes and Raceland), eight lengths of standard, shop coated pipe pieces were instrumented with test wires, galvanic anodes and reference electrodes to facilitate electrical and electrochemical measurements. Field data were collected over time at various corrosion protection current densities based upon E log I polarization studies at each of the research/test sites. Long term polarization testing established the current demand of DIP in each soil to reduce corrosion to varying degrees.

Complimentary to the field tests were laboratory tests using DIP coupons and soils from all five of the field sites, using 40 pipe samples. The lab procedures included E-log I polarization measurements followed by controlled polarization potential measurements over a two-month period.

For the two-month laboratory polarization studies, the currents were initially set to those corresponding to 75% and 50% of the natural corrosion current. As the test samples polarized over time, the current was controlled through the use of resistors and a potentiostat to maintain the same polarization potential.

Table 3 shows the calculated polarization for the laboratory test samples for three levels of corrosion rate reduction.. The 75% corrosion rate polarization (reduces corrosion by 25%) values range between 0.010 and 0.040 volt. For the 50% corrosion rate (reduces corrosion by 50%), the polarization from the applied current ranged from 0.020 to 0.060 volt. The values to achieve -0.850 volt criterion (NACE RP-01069) are much higher (between 0.100 and 0.750 volt). Most of these values are well above the 0.100 V of polarization that is sometimes used in pipeline protection. This illustrates that corrosion is being reduced on the DIP at polarization levels less than typical industry norms.

Collectively, the data from the field (soil) and laboratory (soil and aqueous) evaluations establish a solid first-order basis for corrosion protection design strategies for real-world applications.

Research Summary

The field and laboratory evaluations have been based on the applicability of service life extension strategies where a cathodic corrosion protection current of sufficient magnitude is applied to the pipe. The magnitude of this current is sufficient to practically reduce corrosion rates, but not necessarily approaching zero, as is the case with traditional corrosion control schemes using cathodic protection for regulated pipelines. The use of this corrosion protection solution for DIP is to be based upon a comprehensive engineering evaluation of the likelihood of corrosion and consequences of an external corrosion failure.

A corrosion control strategy based on the use of life extension currents is a well founded engineering approach for typical ductile iron water main projects where some corrosion deterioration is acceptable relative to pipeline reliability and controlled operating costs. Complete cathodic protection requires a notably higher current demand resulting in more cathodic protection hardware and greater costs.

Figures 4 through 7 graphically present key results from the evaluation based on the controlled field and laboratory studies in different soil environments. Figures 4 and 5 respectively show the field and laboratory polarization versus calculated corrosion rate reduction trends. Figure 6 relates polarization to applied corrosion protection current for the field test pipes after a 2 to 3 month stabilization period. Figure 7 summarizes coating resistance characteristics based on the field data.

Table 3: Summary of Laboratory Polarization Tests

Sample	Potential Shift (V) for 75% Corrosion Rate	Potential Shift (V) for 50% Corrosion Rate	Potential Shift (V) for -850 mV Criteria
Spanish Fork, UT			
Bare	0.020 - 0.021	0.047 - 0.050	0.196 - 0.201
Old Thick	0.016 - 0.016	0.037-0.038	0.315 - 0.498
Old Thin	0.016 - 0.028	0.038 - 0.068	0.236 - 0.280
New Thin	0.012 - 0.015	0.029 - 0.036	0.261 - 0.450
Everglades, FL			
Bare	0.016 - 0.024	0.039 - 0.058	0.319 - 0.522
Old Thick	0.012 - 0.013	0.029 - 0.029	0.328 - 0.575
Old Thin	0.008 - 0.016	0.020 - 0.020	0.313 - 0.324
New Thin	0.011 - 0.020	0.026 - 0.026	0.484 - 0.610
Hughes, AR			
Bare	0.015 - 0.026	0.036 - 0.063	0.621 - 0.753
Old Thick	0.014 - 0.027	0.034 - 0.065	0.458 - 0.683
Old Thin	0.018 - 0.021	0.043 - 0.050	0.622 - 0.648
New Thin	0.020 - 0.038	0.049 - 0.093	0.458 - 0.522
Raceland, LA			
Bare	0.015 - 0.015	0.036 - 0.036	0.214 - 0.383
Old Thick	0.015 - 0.020	0.037 - 0.047	0.291 - 0.661
Old Thin	0.014 - 0.016	0.034 - 0.038	0.108 - 0.618
New Thin	0.016 - 0.019	0.039 - 0.046	0.166 - 0.377
Orange, CA			
Bare	0.012 - 0.021	0.029 - 0.050	0.387 - 0.450
Old Thick	0.025 - 0.025	0.038 - 0.060	0.516 - 0.669
Old Thin	0.012 - 0.012	0.028 - 0.030	0.606 - 0.684
New Thin	0.014 - 0.014	0.032 - 0.040	0.621 - 0.718

Cathodic Polarization

Figures 4 and 5 show that a reasonably consistent polarization change of 0.060 to 0.080 volt equates to a quadrupling of pipe service life based on the short duration E-log I polarization studies (~1 hour). The trend lines in these figures are based on the eight test pipes at each of the DIPRA research sites evaluated and can also be used to estimate the level of polarization necessary to realize other service life extensions. For comparison, referencing Figure 4 (field data), to achieve a -0.85 volt polarized pipe to soil potential typically corresponds to a net polarization change on the order of 0.20 to 0.35 volt, or in excess of about 3 times that for a quadrupling of service life.

For a given corrosion current and applied cathodic current, the short duration E-log I data yields corrosion reducing polarization (potential) changes that are less than extended procedures that are more representative of field applications. This is due to the fact that the short duration procedures can only reflect activation polarization and not the longer term protective effects of concentration polarization. Recognizing this, a 0.07-volt polarization “criterion” is a good, reasonably conservative, starting point for formalizing the life extension concept for DIP based on traditional data collection and analysis procedures. With some additional, documented field experience on ductile iron pipelines, it will be possible to refine this guideline.

Figure 6 graphically summarizes the “as-found” current density and polarization data for the field test pipes at the end of the extended testing. In most of the field test cases, a corrosion protection current of 0.1 microampere per square centimeter (~0.1 milliampere per square foot) of total pipe surface results in cathodic polarization levels in excess of 0.07 volt. This, then, is the magnitude of polarization needed for a 75% reduction in the natural corrosion currents or a quadrupling of pipe service life.

Based upon the data and field experience elsewhere, there is sufficient foundation for use of this magnitude current density (0.1 microampere per square centimeter) for corrosion protection designs to realize a practical life extension for DIP in most environments. Typical industry design practice for cathodically protecting ductile iron pipe without a bonded coating is to use a design current density of at least 1 microampere per square centimeter (~1 milliampere per square foot) of total pipe surface, or at least 10 times greater than derived from this evaluation.

Electrical Resistance of Standard Asphaltic Shop Coating

Coating resistance, often expressed in ohms-square feet, is a normalized measure of the resistance-to-earth of underground structures. For standard asphaltic shop coated field test pipes there is a defined (linear) relationship between coating resistance and soil resistivity (see Figure 7). The coating resistance/soil resistivity relationship defined in Figure 7 is a tool that should be used in designing corrosion protection systems relative to electrical attenuation and other design considerations. The dashed line on Figure 7 corresponds to the theoretical “coating resistance” for an uncoated pipe based on an accepted formula by H.B. Dwight for a buried horizontal electrode. Except for perhaps very low soil resistivities where pipe geometry and other factors can control the electrical circuits, the measured resistances for asphaltic shop coated test pipes are typically 1.4 to 1.5 times greater than for uncoated pipe based on the theoretical calculations.

The laboratory tests on eighty, 6 centimeter diameter samples from asphaltic shop coated production pipe suggest limited random areas of any given pipe piece may have a higher coating resistance than the effective (average) values determined from the field test pipes. While this observation is worth noting, the coating resistance/ soil resistivity relationship defined in Figure 7 is considered more representative of actual pipelines and is consistent with field experience. The coating resistances may decrease over time as the asphaltic coating ages. However, this decrease is expected to be subtle with no major impact on coating electrical properties relative to the application of a corrosion protection current.

Corrpro’s evaluation of the standard asphaltic coating shows there is value of the coating in reducing corrosion protection currents. The protective value of this coating, as well as the annealing oxide, is often not considered in corrosion protection for DIP

3. ADDITIONAL FACTORS FOR CORROSION PROTECTION DESIGN

The results of our research and the following key additional factors were collectively used as the foundation for the development of the DIP corrosion protection design decision model presented in Section 4 of this paper. These additional factors include:

- Issues with bonded coatings.
- Information gathered from DIPRA’s database.
- The use of polyethylene encasement for corrosion protection.

Bonded Coatings on Ductile Iron Pipe

Industry experience by users, engineers, coaters and manufacturers demonstrates that dielectric coatings are not a practical or cost effective corrosion control method for DIP, with or without the use of corrosion protection currents, for most typical and atypical applications. The basis for this is simple – the costs for the bonded coating are high and there are other more practical and effective corrosion control techniques that can be implemented at a considerably lower Total Cost of Ownership (TCO). The key to determining which lower cost methodology to use requires a good understanding of the likelihood and consequences of corrosion.

In addition to high costs, some of the factors that limit the effectiveness of a bonded coating for ductile iron pipe include:

- Abrasive blast surface preparation negates the protective effects afforded by the asphaltic shop coating and the annealing oxide.
- Inability for proper surface preparation and coating adhesion relating to the peen pattern and the annealing oxide.
- Pipe (substrate) damage, including blisters and slivers when abrasive blasting.
- Limited shop coating applicators.
- Lack of familiarity of many water/wastewater pipe installation contractors and inspectors relative to proper handling of coated ductile iron pipe.
- Field coating procedures for joints, restrained joint assemblies and repairs.
- Impact of the coating on joint configurations, joint tolerances and field cut pipe.

The concept that bonded coatings are not appropriate for DIP is contrary to the opinions and common practices of many corrosion control practitioners that promote the use of bonded coatings, typically in conjunction with cathodic protection. The only AWWA Standards for coatings on ductile iron pipe are ANSI/AWWA C105/A21.5 for polyethylene encasement and the ANSI/AWWA C151/A21.51 pipe standard which includes the standard, asphaltic shop coat. AWWA and SSPC standards sometimes used to specify surface preparation and coatings for DIP were developed for steel pipe and are not appropriate for DIP. Furthermore, development of effective standards for bonded coatings on DIP would be difficult at best, and, at worst would imply acceptance of a corrosion protection solution that is not practical.

Analysis of DIPRA Database

Historical records of corrosion maintained by DIPRA on iron pipe have been primarily in paper format, having been collected on a project-by-project basis. During this collaborative effort, the data has been entered into a computerized database using Microsoft Access. The initial database includes 1297 investigations. Results from 82 additional pipe inspections have been included over the last two years for a total of 1379 records with over 60,000 bytes of information.

The database has been analyzed by a professional statistician to identify trends. Some of the key findings from the analysis of the database include:

- The pitting rate of ductile iron is somewhat less than gray cast iron, and to an extent, soil specific. In general, the corrosion rates for gray and ductile iron can be considered the same.
- Polyethylene encasement is of value as a corrosion control method.

Continual updating and analysis of the database will be made for periodic reviews of the “living” procedures developed under this program. DIPRA will be publishing detailed results of the database in a separate technical paper.

Polyethylene Encasement

The analysis of the database coupled with documented case histories support the value of polyethylene encasement as a corrosion control method. Initial tests were performed in 1951 and since then, polyethylene encasement has been installed on thousands of miles of iron pipe. Use of polyethylene encasement is both cost effective and technically sound. Similar to other corrosion control solutions, the decision to use polyethylene encasement should be based on corrosivity factors and the consequences of corrosion failures.

The use of corrosion protection currents improves the effectiveness of polyethylene encasement by protecting the pipe where the film was damaged or not properly applied resulting in uncovered surfaces. The methods are not exclusive and there is synergy when used in combination.

Further work is needed to assure that materials and installation practices are in compliance with ANSI/AWWA C105/A21.5. Industry needs to improve construction practices and the quality of the polyethylene encasement installation. Specifications can and should be written to affect these improved practices, particularly in high risk and high consequence areas.

4. CORROSION PROTECTION DESIGN DECISION MODEL

Figure 8 presents the corrosion protection design decision model developed over the last two years by a nine member professional Technical Resource Team (TRT). The TRT is comprised of engineering staff from Corpro Companies, Inc., DIPRA, and DIP manufacturers. The design decision model is based on the extensive experiences of the nine individuals involved, with a combined professional know-how of over 200 years.

Common design practices, including the use of the ANSI/AWWA C-105/A21.5 10-point system, typically evaluate only the likelihood of corrosion deterioration. The two dimensional decision model in Figure 8 is an extension of the 10-point system that considers the consequences of a corrosion failure as well as the likelihood of corrosion. As utilities continue to look for processes to maximize their return on investment and acknowledge a decaying infrastructure with limited resources for upgrades or replacement, this addition is considered essential to sound corrosion engineering design in today's cost conscious environment.

The design decision model is applicable to DIP transmission and distribution design projects. The contributing likelihood factors are determined by the collection and analysis of soil samples, and can result in a likelihood "point score" of 50 or more points. The particular likelihood factors include:

- Resistivity/conductivity
- Moisture content.
- Groundwater influence.
- pH.
- Chloride ion concentration.
- Sulfide ion concentration.
- Redox potential.
- Bi-metallic connections that could contribute to increased pipe corrosion rates.
- Presence of a known corrosive environment, e.g. cinders, mine waste, peat bog, landfill, fly ash, or coal.

The contributing consequence factors that can total up to a point score of 50 points include:

- Pipe diameter.
- Pipe repair considerations.
- Depth of cover.
- Availability of alternate water supply.

The likelihood and consequence factors collectively determine a corrosion control strategy that could include one or more of the following key scenarios:

- As manufactured, with standard asphaltic shop coating.
- Polyethylene encasement.
- Polyethylene encasement with pipe joint bonding.
- Life extension corrosion protection, with or without polyethylene encasement.
- Cathodic protection.

Typically, the likelihood and consequence factors will be determined at intervals of 1,000 to 1,500 feet along a proposed pipeline route. An engineering analysis will then be made to determine the suitability of one or more corrosion control treatments for the various sections of the project. The intent of the decision model is to thoroughly weigh the likelihood and consequence considerations section by section, rather than to make the most conservative recommendations for the entire project. Where stray earth currents are expected to impact the piping, project specific additional corrosion control methods are to be employed.

5. CONCLUSIONS

- Corrpro and DIPRA are jointly developing a program consisting of an improved protocol for testing the soil and determining the likelihood of corrosion, and a corrosion protection design decision model for ductile iron pipe.
- The program has been developed through a joint effort of DIPRA and Corrpro which consisted of:
 - Compilation and analysis of DIPRA and Corrpro pipe inspection databases.
 - Performance of laboratory testing to evaluate properties of standard, asphaltic shop coat and cathodic polarization characteristics.
 - Field inspections of ductile iron pipe.
 - Field testing of corrosion rates, corrosion protection current requirements and cathodic polarization characteristics.
 - Joint field investigation for the design of new pipeline projects.
 - Soil test procedure comparison.
 - Analysis of DIPRA and Corrpro test results on soil samples splits.
 - Shared corrosion experience and technical know-how.
- The standard, asphaltic shop coating and typical annealing oxide provide some degree of corrosion protection for ductile iron pipe.
- The measured resistance to earth of shop-coated pipe is 1.4 to 1.5 greater than uncoated pipe.
- Bonded, dielectric coatings are not a cost-effective solution for corrosion protection of ductile iron pipe and are not included in the design decision model.
- Polyethylene encasement is a cost effective and technically sound method for corrosion protection of ductile iron pipe and has an important place in the program.
- Cathodic currents improve the effectiveness of polyethylene encasement. The methods are not exclusive and can be used in combination.

- An important element of the program is enhanced QA and QC in polyethylene encasement materials and construction practices.
- A 75% reduction in corrosion rate or four times life extension of DIP can often be realized with 0.07 volt or less of polarization.
- In many soil environments, 0.07 volt of polarization can be achieved at current densities of 0.1 microampere per square centimeter (100 $\mu\text{A}/\text{ft}^2$).
- The objective of the program outlined herein is to control corrosion to rates that achieve a useful life of 75 to 100 years.
- The program comprehensively addresses external corrosion of ductile iron pipe.
- When the program is followed, no external corrosion allowance is required when determining pipe class.
- Unlike some other strategies, this program addresses the consequences of corrosion failure as well as the likelihood of corrosion.
- Use of the program can result in considerable corrosion control cost savings when compared to many existing procedures.

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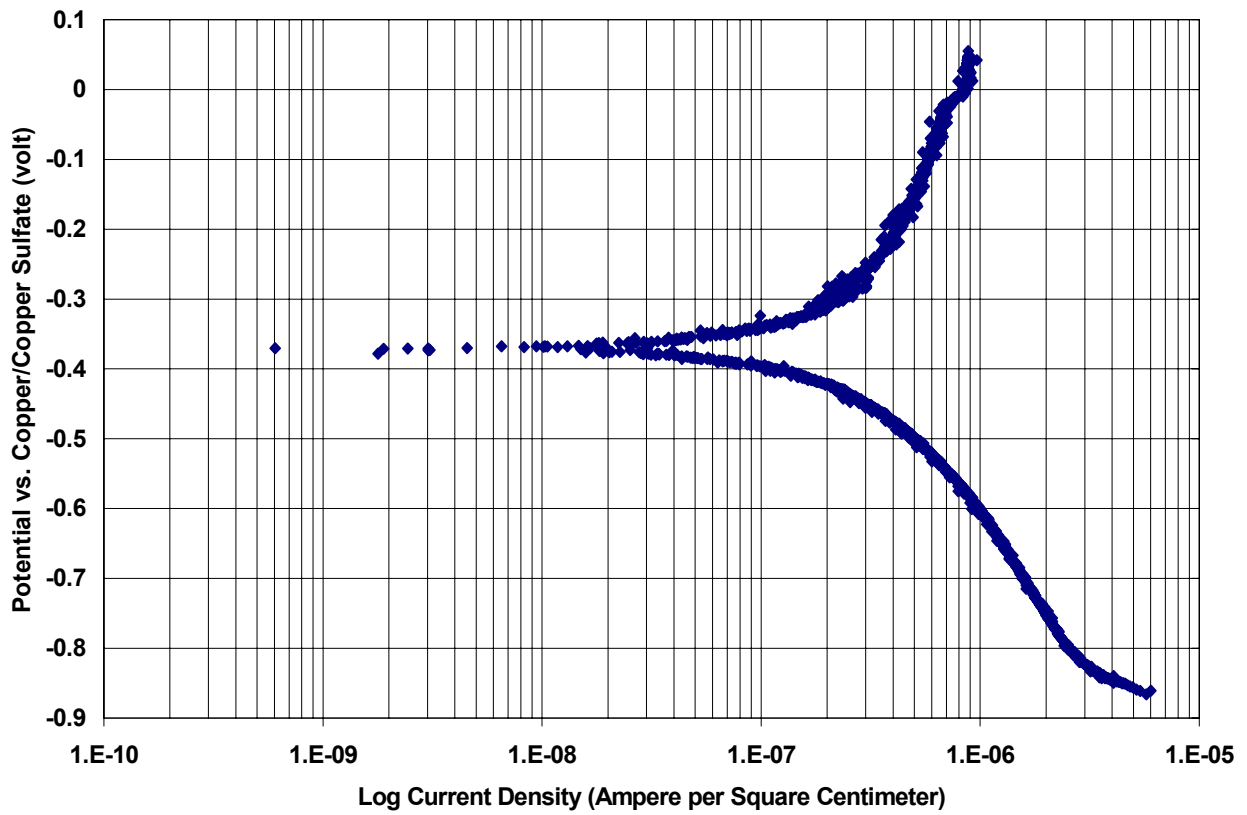


Figure 1: Typical E-logI Scan

E-logI Plot with Cathodic and Anodic Slopes

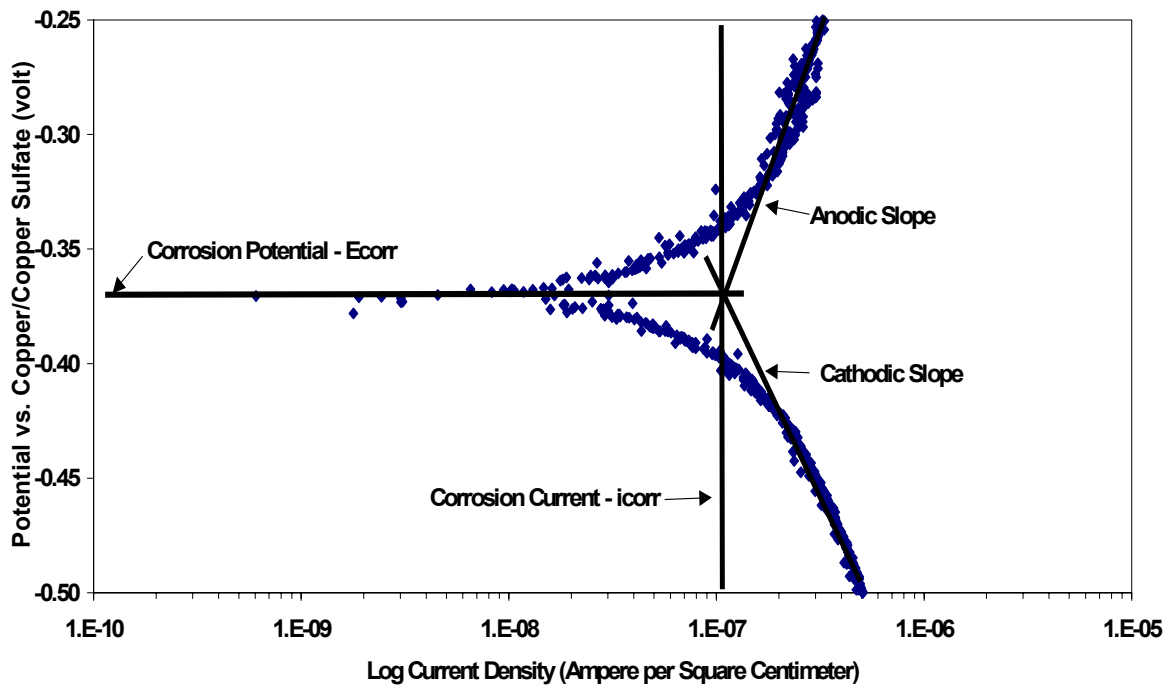


Figure 2: E-logI Scan Analysis

Graphical Analysis

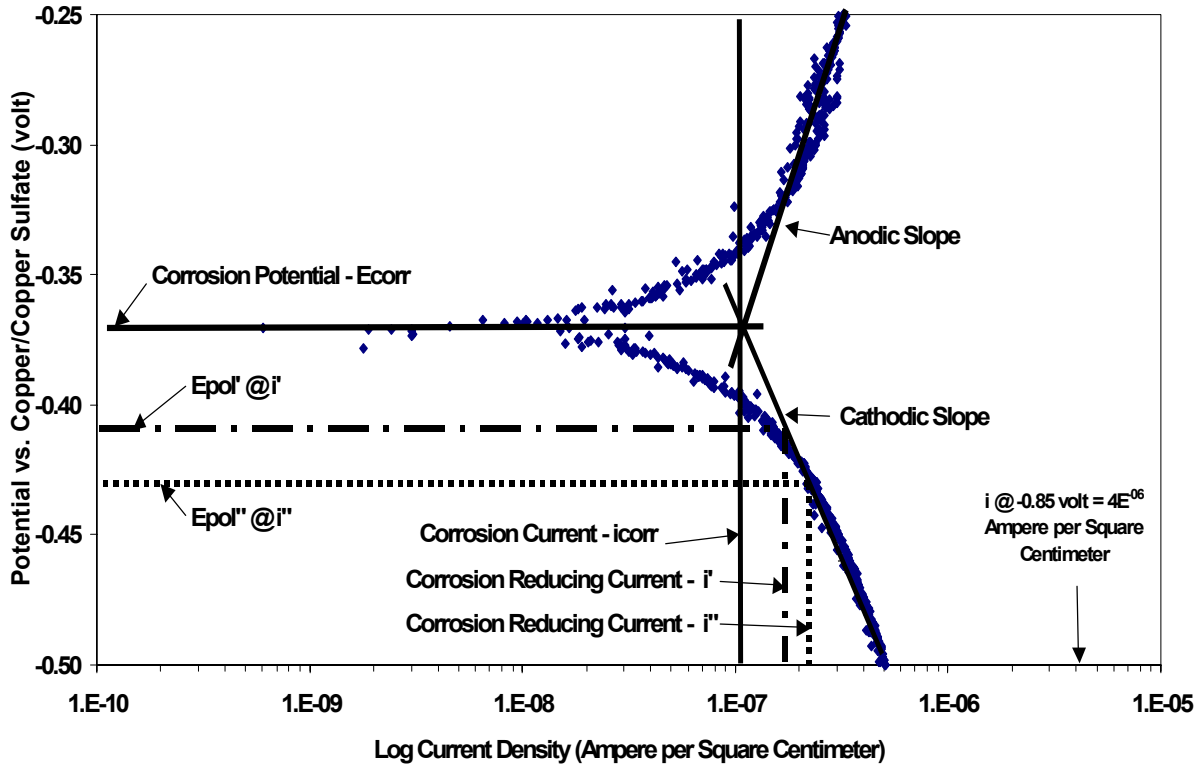


Figure 3: Determination of Corrosion Reduction Current and Potential

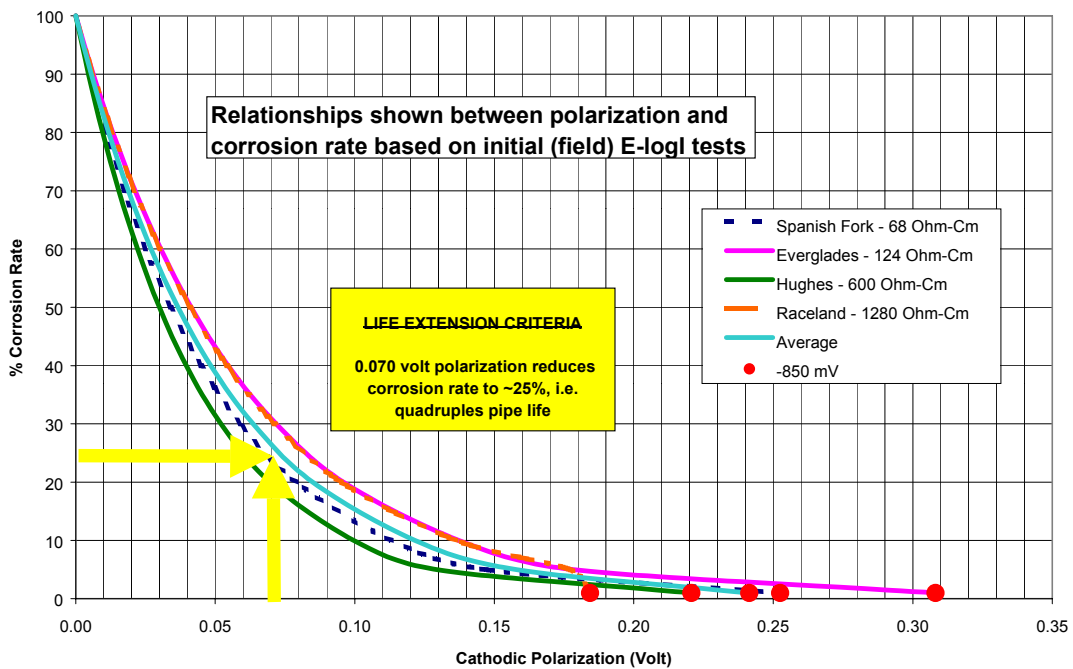


Figure 4: Polarization versus Corrosion Rate Reduction (Field Tests)

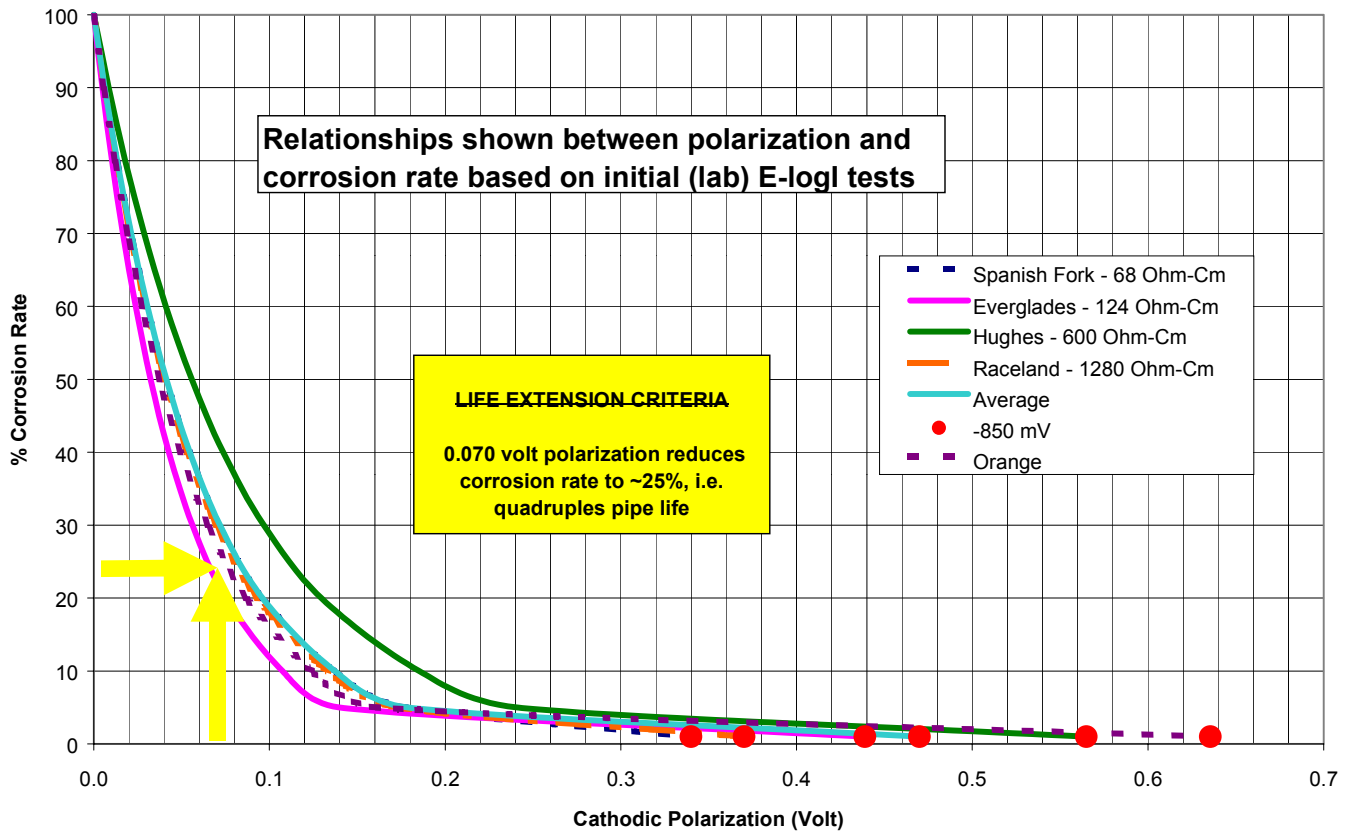


Figure 5: Polarization versus Corrosion Rate Reduction (Lab Tests)

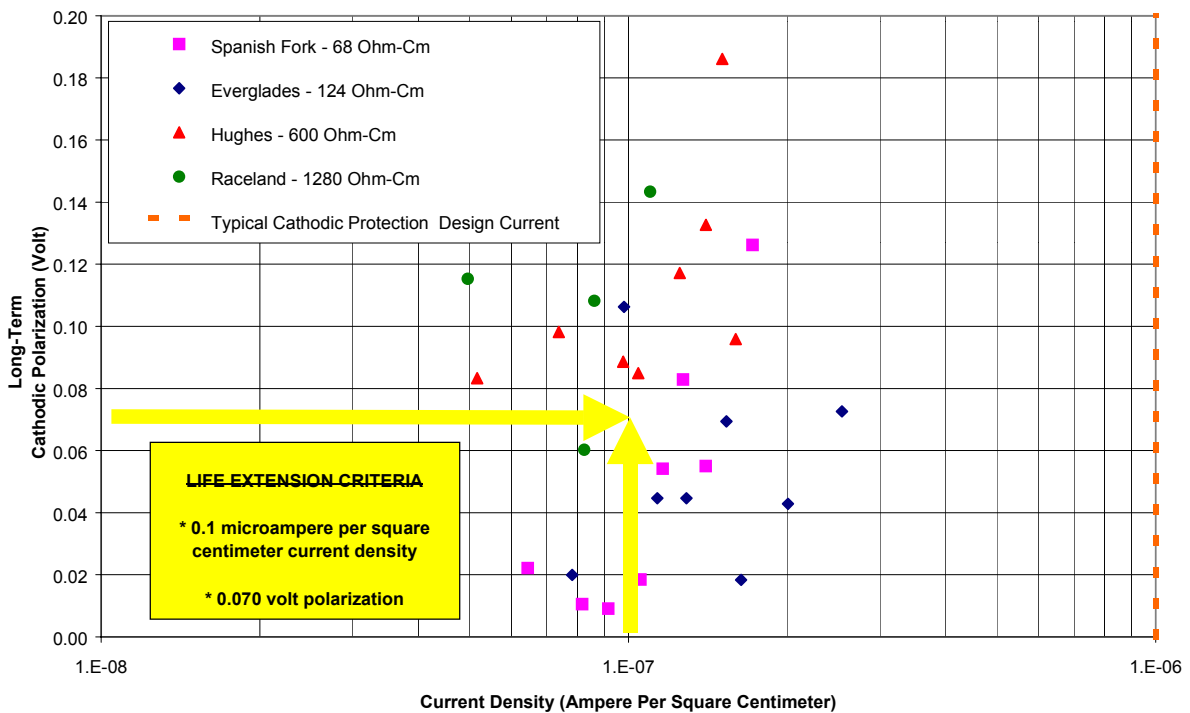


Figure 6: Long Term Polarization versus Corrosion Protection Current Density

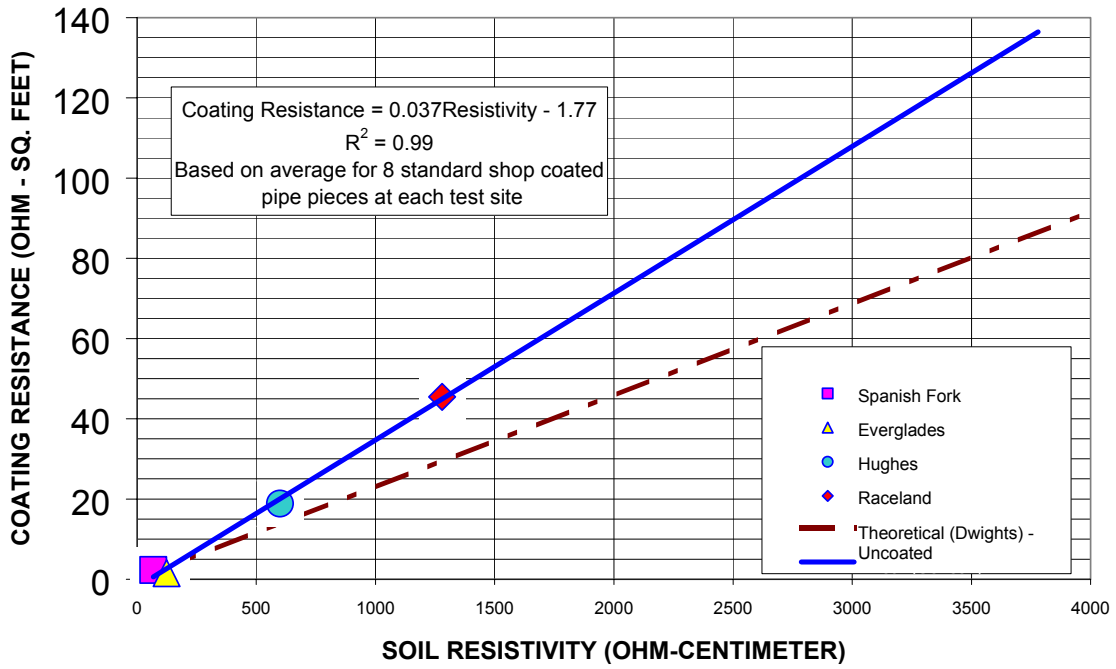


Figure 7: Field Coating Resistance versus Soil Resistivity

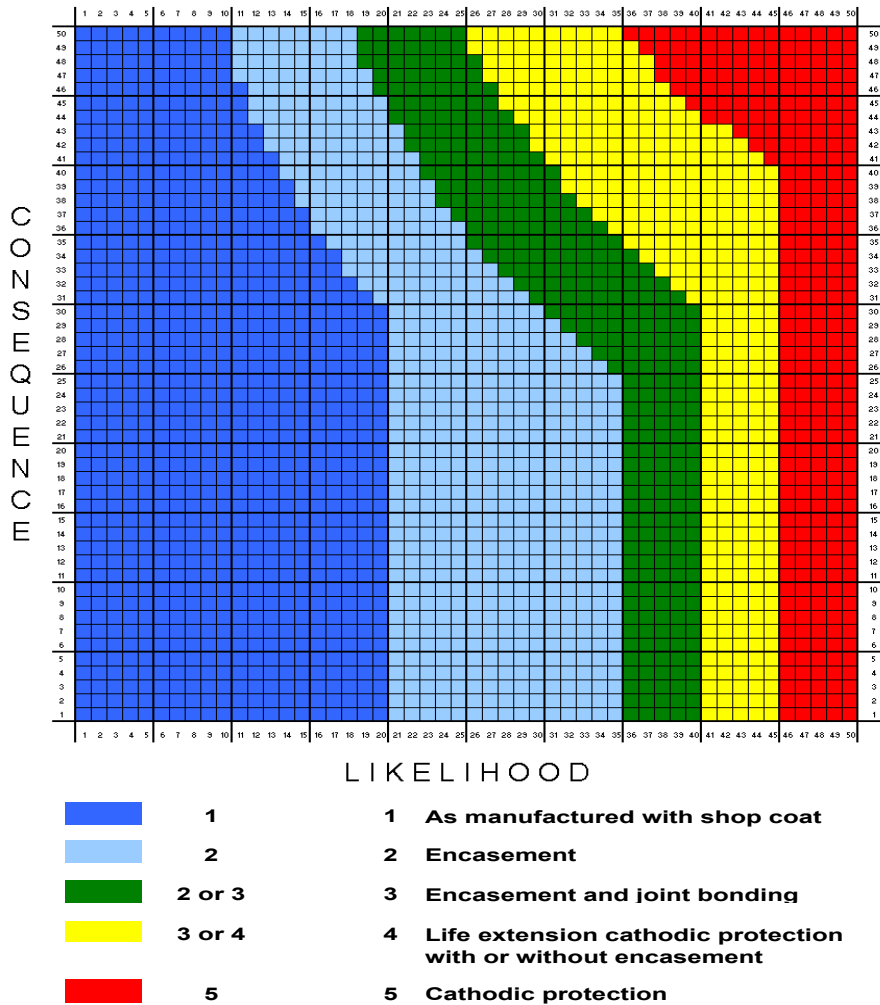


Figure 8: Design Decision Model