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# Performance of External Pipeline Coatings in Low Temperature Conditions

Mark Yunovich
Honeywell International, Inc.
14503 Bammel – N. Houston Rd., Houston, TX 77014, USA
Mark.Yunovich@honeywell.com

Colin Scott, Robert Denzine
CC Technologies, Inc., a DNV Company
5777 Frantz Road, Dublin, OH 43017, USA
Colin.Scott@dnv.com
Robert.Denzine@dnv.com

## Abstract

There is a tacit concern in the oil and gas industry regarding hazards of excessive cathodic protection (CP) on pipelines. Research has shown that at ambient temperatures, overprotection may lead to cathodic disbondment (CD) of external coatings. The relationship between pipeline CD and CP overprotection at low temperatures was investigated by employing CD tests on fusion-bonded epoxy (FBE)-coated samples in either soil or salt solutions, subjected to different potentials, and subjected to freeze only or freeze/thaw cycles. The study has highlighted both beneficial and detrimental effects of low temperatures; it has been demonstrated that freeze / thaw cycles can exacerbate coating disbondment. While the preliminary results indicated that, in order to reduce the risk of CD, maximum applied CP level should be approximately -1050 mV (CSE), the testing was not extensive enough to consider this as fixed criterion for design of systems.

**Keywords:** cathodic protection, overprotection, disbondment, arctic, low temperature, fusion bonded epoxy (FBE)

## Introduction

There is a tacit concern in the oil and gas industry regarding hazards of excessive cathodic protection (CP) on pipelines. Research has shown that at ambient temperatures, overprotection may lead to cathodic disbondment (CD) of external coatings and increased susceptibility to hydrogen induced damage; however, whereas increasing the hazard of hydrogen-induced damage to steel for a given potential, lower temperatures are expected to retard CD. A recently completed 2-year research study (co-funded by the US Department of Transportation (USDOT) and the Pipeline Research Council International (PRCI) provoked considerable discussion with regard to the effects of temperature on both cathodic disbondment of external coatings and damage to steel by hydrogen[1]. Also, industry publications cite renewed momentum to transport natural gas from Alaska's North Slope, which would require construction of new pipelines, both onshore and offshore.

## Objectives and Experimental Approach

The primary objective of this project was the investigation of the effect of excessive CP on coating disbondment at low temperatures. The work involved laboratory-based experimental work and application of existing in-house expertise to optimize the experimental matrix.

### Test Procedure

The testing protocol for cathodic disbondment was a combination of concept and testing parameters used in ASTM G8 and ASTM G95. The approaches of G8 and G95 are similar and consist of applying a negative potential to a coated sample that contains an intentionally introduced defect, for a specified period of time. The specimens, which were prepared specifically for the experimental program, consisted of a carbon steel sheet coated with a fusion bonded epoxy (FBE) coating. The coating thickness ranged from 0.38 to 0.51 mm (15 to 20 mils). The size of the holiday was 6 mm (0.23 in). An example of the coated sample is shown in Figure 1.

The configuration of the cell used for all tests is illustrated in Figure 2. The body of the cell and its components were made of PVC. The cell was attached to the coated test panel with a silicone adhesive and allowed to dry tack-free before filling the cell with the test electrolyte/soil environment. The housing for the Pt/Nb counter electrode was closed with a drilled PVC cap to permit the ionic path between the holiday and the electrode and filled with agar.

### Test Conditions

Tests were conducted in several environments, which included tests in soil from Dublin, Ohio, and water-based 3.5% sodium chloride solution. Each particular combination of a coating and an environment was tested in duplicate. A summary of the test conditions is shown in Table 1.

The target temperature for the low temperature tests was 20°F (-6.7°C). The low temperature test cells were placed in a freezer that was thermostatically controlled. Several test cells were subjected to freeze/thaw cycles of 3 weeks and 1 week duration, respectively. During the thaw portion of the cycle, the test cells were removed from the freezer and allowed to thaw. It was noted that the soil samples remained “slushy” during the thaw cycles. The freezer temperature vs. time profile is shown in Figure 3. Some tests were carried out at room temperature to allow for comparisons.

In tests involving cathodic polarization, the targeted potential magnitudes were similar to the values used in mechanical tests (-850 and -1100 mV (CSE)). Cathodic protection was applied using galvanostatic control with a periodic adjustment of the current to achieve the target potentials; some deviations of the target potentials were observed, which are not deemed critical for the purposes of research.

The overall duration of the cathodic disbondment tests was 139 days. The weighted average temperature was 19°F. Upon completion of the exposure, the cells were taken apart and the surfaces cleaned to remove residual soil particles or salt solution.

### Test Evaluation

After the test, the cells were removed from the coated panels at tested at room temperature. Initial radial cutting of the samples was accomplished using a hand-held utility knife. Four cuts, approximately 4 inches long and 45 degrees apart, were made through the center of the holiday extending to the outer diameter of the test cell, in accordance with CAN/CSA-Z245.20-M92. The knife blade was used to remove (chip off) disbonded coating. The knife blade was slid under the coating, which was pried up until a definite resistance was met.

The extent of cathodic disbondment was evaluated by measuring the average disbondment length on the four diameters, starting from the outside diameter (OD) of the introduced defect, as illustrated in Figure 4 . Each diameter length was measured using digital calipers, and recorded to the nearest 0.1 mil. The recorded disbondment results were used to calculate an average radius of disbondment rounded to the nearest 0.1 mil. The average radius of disbondment is defined as:

$$R_{average} = \frac{R1 + R2 + R3 + R4 + R5 + R6 + R7 + R8}{8}$$

where $R_{average}$ is the average radius of coating disbondment measured in the eight radial directions. The measurement schematic is illustrated in Figure 4.

## Results and Discussion

### Disbondment Measurements

The results of the cathodic disbondment measurements are summarized in Table 2. The ON- and OFF-potential data for each tested coating are also presented. In the case of the tests with no CP applied, the free corrosion potential (FCP) is listed in the OFF-potential column; the data shows *weighted averages* of the measured potentials. An example of detailed potential measurements is shown in Figure 5.

The aggregate data from liquid and soil tests with applied potential is presented as a graph in Figure 6. The linear regression suggests that higher (more negative) potentials are positively correlated with more disbondment for all tested conditions ($R^2 = 0.77$)[1].

Figure 6 can be used to provide a guideline for the maximum CP level that can be used and still provide acceptable coating. NACE PR0394[2] considers a cathodic disbondment radius of 10 mm (0.39 in) or less to be acceptable. The Figure indicates that a disbondment of 10 mm corresponds to an OFF-potential of approximately -1050 mV (CSE). In principle, if the CP levels are kept more positive than this value, the extent of cathodic disbondment should be maintained within the acceptable level. Note that this is a tentative value based on limited data, and should not be applied in service without further validation. A maximum CP potential level of -1100 mV (CSE) is often considered as acceptable for systems at ambient temperatures.

Figure 7 and Figure 8 are plots of the extent of cathodic disbondment for the various test conditions at FCP and under applied cathodic potentials, respectively. For the tests performed at FCP, the greatest disbondment is observed in the test performed in salt solution. For the tests performed in soil, there was less disbondment in the “freeze” test than the “freeze/thaw” cycle test or the room temperature test. This implies that disbondment is less at the low temperature. However, the differences in the three soil tests are minimal, and the effect may not be real. For the tests performed under applied cathodic potentials there is also an increase in disbondment with the freeze/thaw cycle relative to the freeze alone. The effect is minimal at the lower CP level and higher at the higher CP level.

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[1] Note that the linear regression is not theoretically derived, but a simple trendline through the data for comparison purposes. When a similar analysis is attempted with regard to the applied current (or current density estimated using the disbondment area), the fit deteriorates considerably.

It is hypothesized that the freeze/thaw cycle leads to greater disbondment as liquid can penetrate under the coating during the thaw cycle and then freeze, causing expansion forces that further disbond the coating. The data suggests that the freeze/thaw action is enhanced if there is an additional action of the applied high negative potential. The freeze/thaw effect is more pronounced in the samples that have experienced greater disbondment at the freeze-only conditions. Also, as would be expected, the effect is more visible in the liquid environment when compared to tests in soil. In the soil tests, without the concomitant damage from the high potentials, the freeze/thaw effect was negligible.

It was noted during the tests performed in salt solution that the solution did not completely freeze, but remained "slushy" near the steel test sample and coating. The ice forming during the freezing cycle would tend to segregate the salt into the remaining water. If the salt content were high enough, it may prevent the final water from freezing, and instead remaining slushy at the bottom of the test cell. If this were the case, then the mechanism of ice expansion disbonding the coatings would not be valid. However, the increased salt content would raise the electrical conductivity of the slush and may increase the local corrosion rate. This may lead to increased hydroxide formation that would cause further disbondment.

In order to further assess the degree to which temperature and polarization affect disbondment, the above data was compared with the control data that was performed at FCP, as shown in Figure 9. Figure 9 is a chart of the change in disbondment length relative to the tests performed at room temperature and at FCP. In the case of the salt solution the effect of the freeze/thaw cycle was significant. This supports the hypothesized mechanism of disbondment as being associated with liquid penetrating under the coating and the subsequent freezing leading to forces that further disbondment. In the case of the tests performed in soil the effect is less dramatic, and this observation is also consistent with the freeze/thaw mechanism hypothesis. For the test performed at the lower CP level the effect of the freeze or freeze/thaw cycles is minimal. For the tests performed at the higher CP level the effect is significant. The conclusion drawn is that both a high CP level and freeze/thaw cycles can be detrimental to coating integrity.

An important consideration is that the assessment of the hazards of increased cathodic disbondment area at existing holidays at higher CP currents should be considered with regard to the ability of the imposed CP to mitigate corrosion at the larger holiday(s). The fact that the holiday area is increased due to overprotection does not necessarily imply that this location will no longer be cathodically protected. For example, Worthingham et al[3] indicates that fusion bonded epoxy (FBE) fails in a "CP-friendly manner" and concludes that "as long as CP is operating on a pipeline, blistering and disbondment of FBE coatings does not present an integrity threat to the pipeline". Note that the study evaluated the performance of FBE coatings only. However, if the conditions of overprotection persist over an extended area of the pipeline, it is possible that with time CP output may not be sufficient for an effective CP protection. Further work is required to address the issue.

## Conclusions

- The results confirm the commonly accepted trend that the increase in the applied cathodic protection current leads to increased cathodic disbondment of the coatings.
- Coating disbondment appears to be less at lower temperatures relative to room temperature, for tests performed at FCP. This is beneficial from the perspective of integrity.

- The salt solution led to greater cathodic disbondment than the soil slurries. The liquid is more able to penetrate into the bonded interface than the soil.
- A freeze/thaw cycle exacerbates disbondment relative to a freeze alone. It is hypothesized that this is due to liquid penetrating into the interface during the thaw cycles, followed by expansion forces during the freezing that further disband the coating. This mechanism is yet to be confirmed. The effect seems to be exacerbated by high CP levels. This is detrimental from the perspective of integrity for systems in moderate climates that are subjected to variable weather conditions.
- The data can be used to develop a tentative maximum CP level to mitigate cathodic disbondment of -1050 mV (CSE).

The above conclusions highlight some beneficial and some detrimental effects of low temperatures on cathodic protection. While the preliminary results indicate the guideline on maximum CP level applied should be reduced, the testing is not extensive enough to consider this as fixed criterion for design of systems.

The experimentation described above can be considered exploratory. The development of rigorous guidelines would require further testing to explore the effects of time, as the tests performed were short-term and damage may be exacerbated given sufficient reaction time.

Note that the effects of low temperatures on the hydrogen-induced damage to linepipe steels were not part of this investigation.

## References

1. "Effect of High CP Potentials on Pipelines", CC Technologies report R3189-01R, November 2004.
2. NACE PR0394 "Application Performance and Quality Control of Plant-Applied Fusion Bonded Epoxy External Pipe Coating"
3. R. Worthingham and M. Cetiner, "Long Term Performance of Fusion Bonded Epoxy Coated Pipelines", International Pipeline Conference, Calgary, Alberta, Canada, 2004, IPC 04-0570.

**Table 1. Summary of test conditions.**

| Environment | Target Temperature | Target potential | Conditions |
|---|---|---|---|
| Soil | Room | FCP | -- |
| Soil | 20°F (-6.7°C) | FCP | Freeze |
| Soil | 20°F (-6.7°C) | FCP | Freeze/Thaw |
| Soil | 20°F (-6.7°C) | -850, -1100 | Freeze |
| Soil | 20°F (-6.7°C) | -850, -1100 | Freeze/Thaw |
| NaCl | Room | FCP | -- |
| NaCl | 20°F (-6.7°C) | -1100 | Freeze |
| NaCl | 20°F (-6.7°C) | -1100 | Freeze/Thaw |
| | | Total tests (with duplicates) | 20 |

**Table 2. Summary of cathodic disbondment tests.**

| Sample | Potential, V | | Average Disbonded Diameter, inches |
|---|---|---|---|
| | ON | OFF/FCP | |
| Soil Control Room Temperature 1 | - | -0.767 | 0.230 |
| Soil Control Room Temperature 2 | - | -0.78 | 0.129 |
| Soil Control Freeze 1 | - | -0.624 | 0.051 |
| Soil Control Freeze 2 | - | -0.617 | 0.181 |
| Soil Control Freeze Thaw 1 | - | -0.67 | 0.221 |
| Soil Control Freeze Thaw 2 | - | -0.663 | 0.101 |
| Soil Low Potential Freeze 1 | -1.201 | -0.894 | 0.158 |
| Soil Low Potential Freeze 2 | -1.04 | -0.857 | 0.195 |
| Soil Low Potential Freeze Thaw 1 | -1.208 | -0.894 | 0.284 |
| Soil Low Potential Freeze Thaw 2 | -1.083 | -0.851 | 0.087 |
| Soil High Potential Freeze 1 | -1.865 | -1.184 | 0.219 |
| Soil High Potential Freeze 2 | -2.15 | -1.157 | 0.371 |
| Soil High Potential Freeze Thaw 1 | -2.062 | -1.158 | 0.446 |
| Soil High Potential Freeze Thaw 2 | -1.805 | -1.188 | 0.681 |
| NaCl Control Room Temperature 1 | - | -0.753 | 0.602 |
| NaCl Control Room Temperature 2 | - | -0.753 | 0.696 |
| NaCl High Potential Freeze 1 | -2.354 | -1.291 | 0.493 |
| NaCl High Potential Freeze 2 | -2.11 | -1.218 | 0.810 |
| NaCl High Potential Freeze Thaw 1 | -2.027 | -1.33 | 0.885 |
| NaCl High Potential Freeze Thaw 2 | -1.962 | -1.303 | 1.035 |

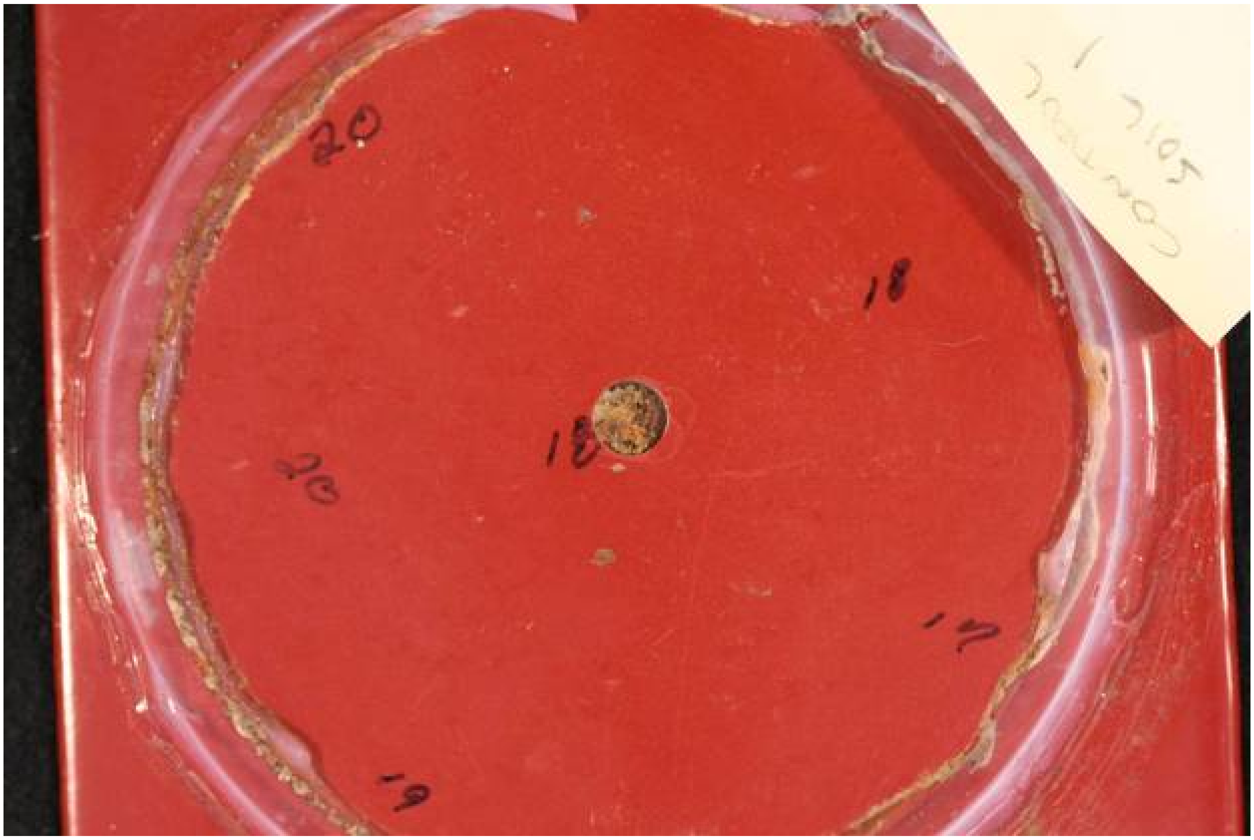

**Figure 1. Appearance of the test sample (coating thickness ranges from 17 to 20 mils).**

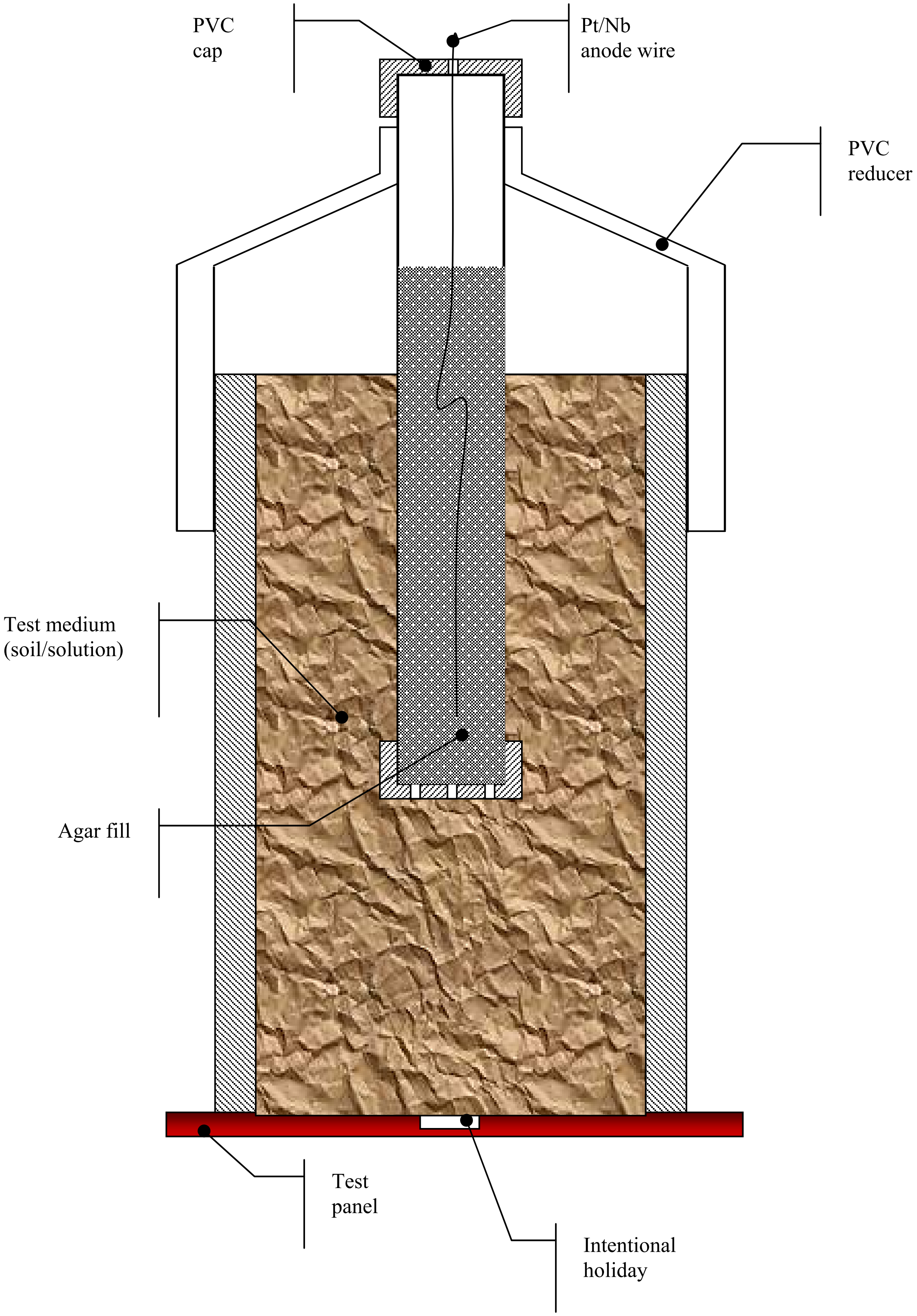

Figure 2. A schematic of the test cell and probe.

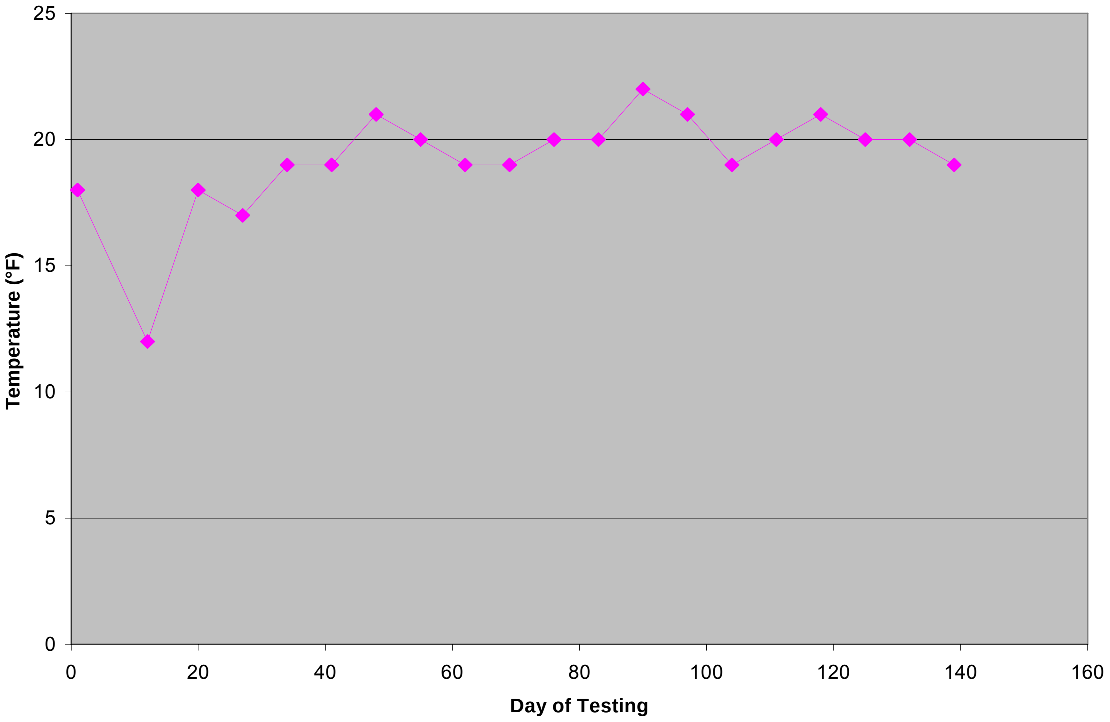

Figure 3.  Test temperature versus time for the freeze and freeze/thaw cycle tests.

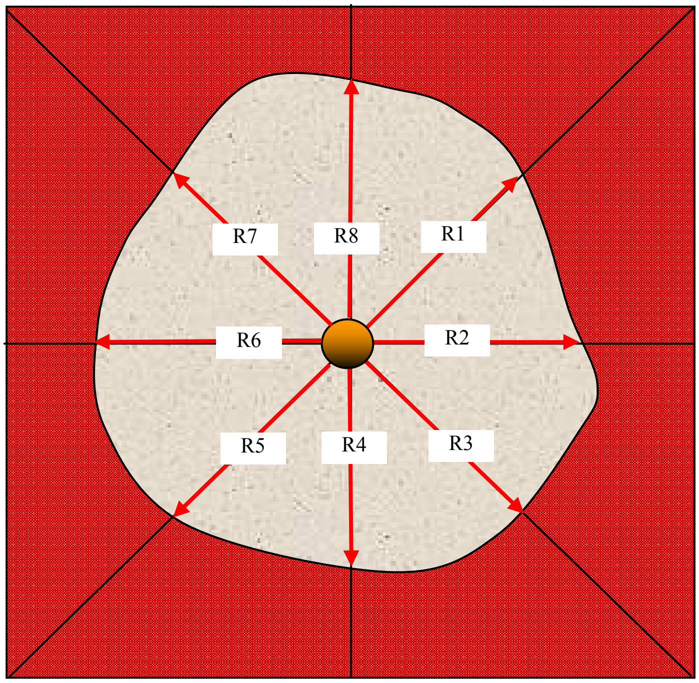

Figure 4.  Disbondment distance measurement schematic.

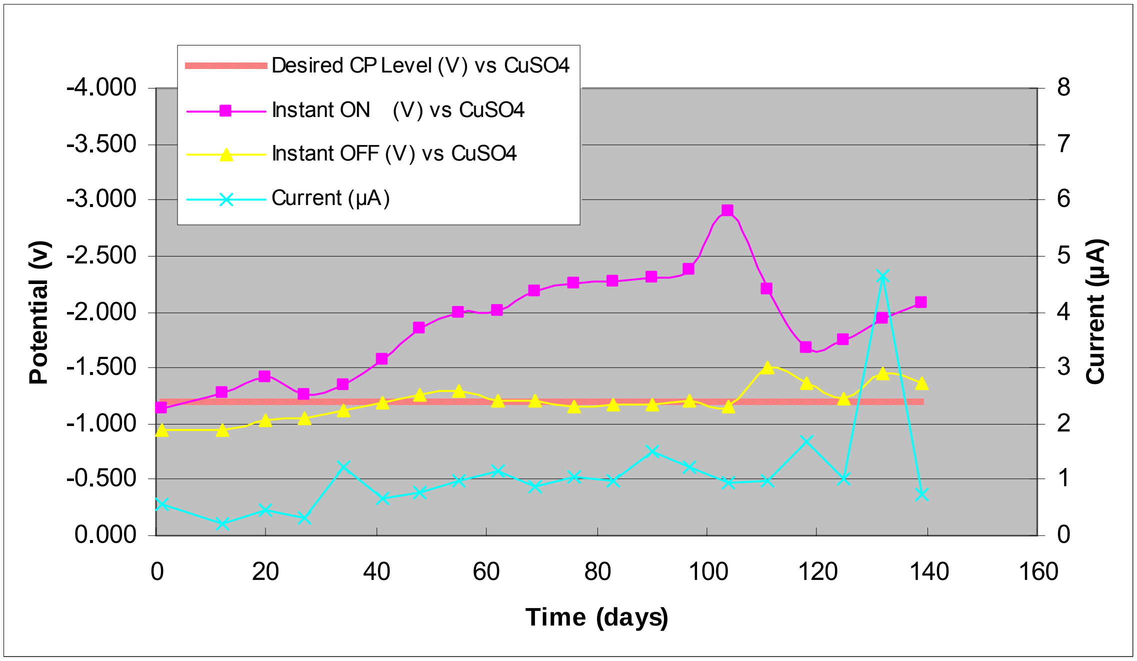

Figure 5. - Soil High Potential Freeze 1

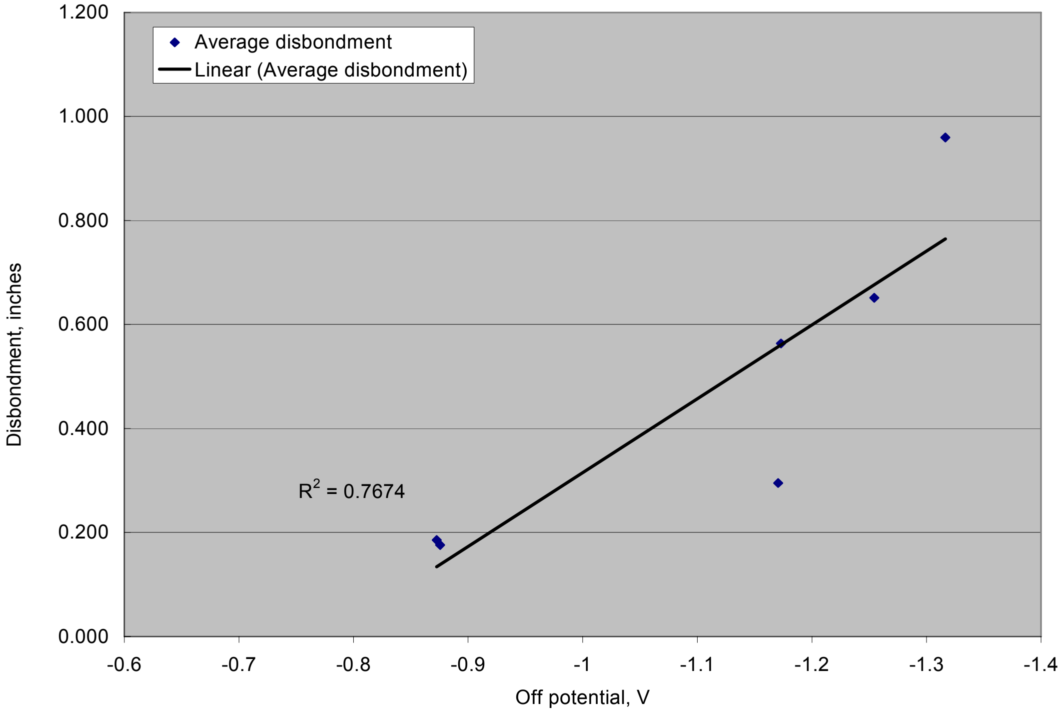

Figure 6. Cathodic disbondment vs. OFF potential values (averaged data).

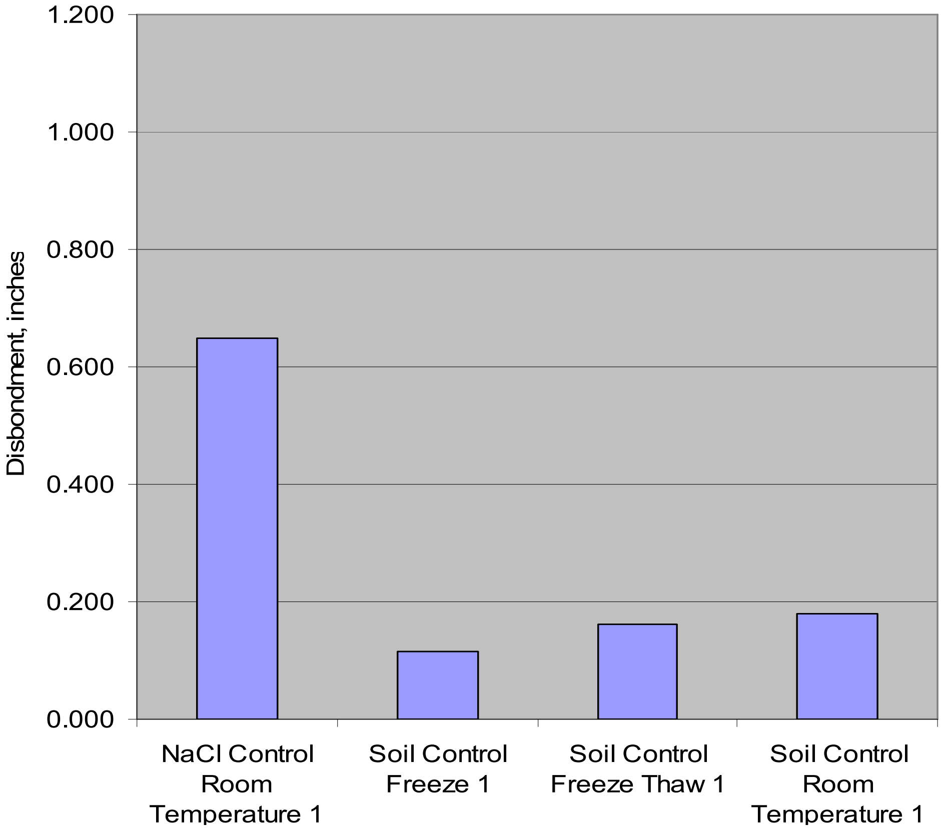

**Figure 7. Extent of cathodic disbondment for tests performed at FCP.**

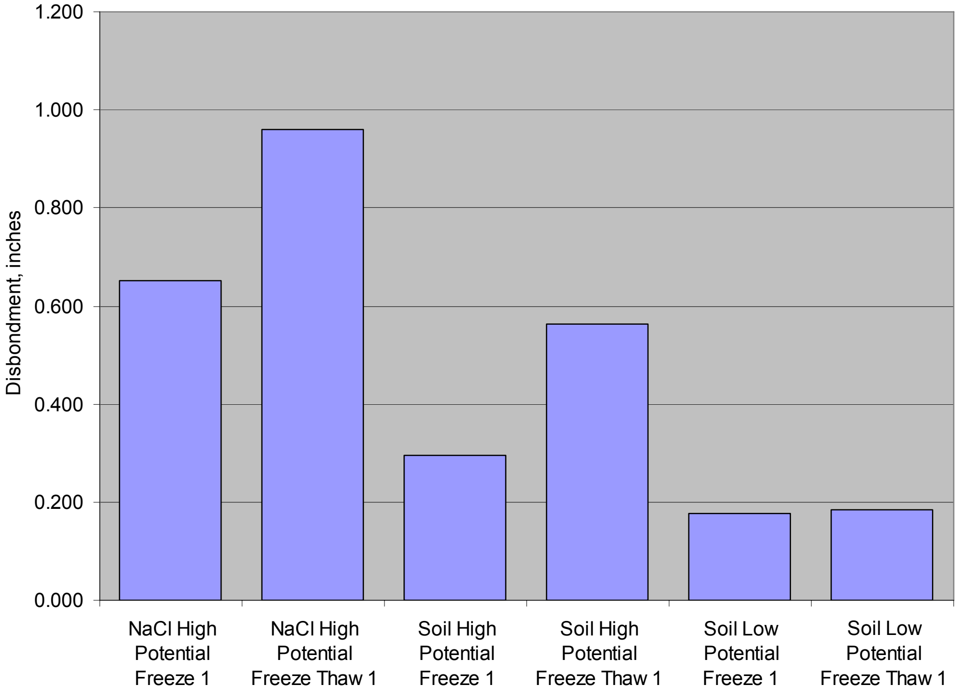

**Figure 8. Extent of cathodic disbondment for tests performed with applied cathodic potentials.**

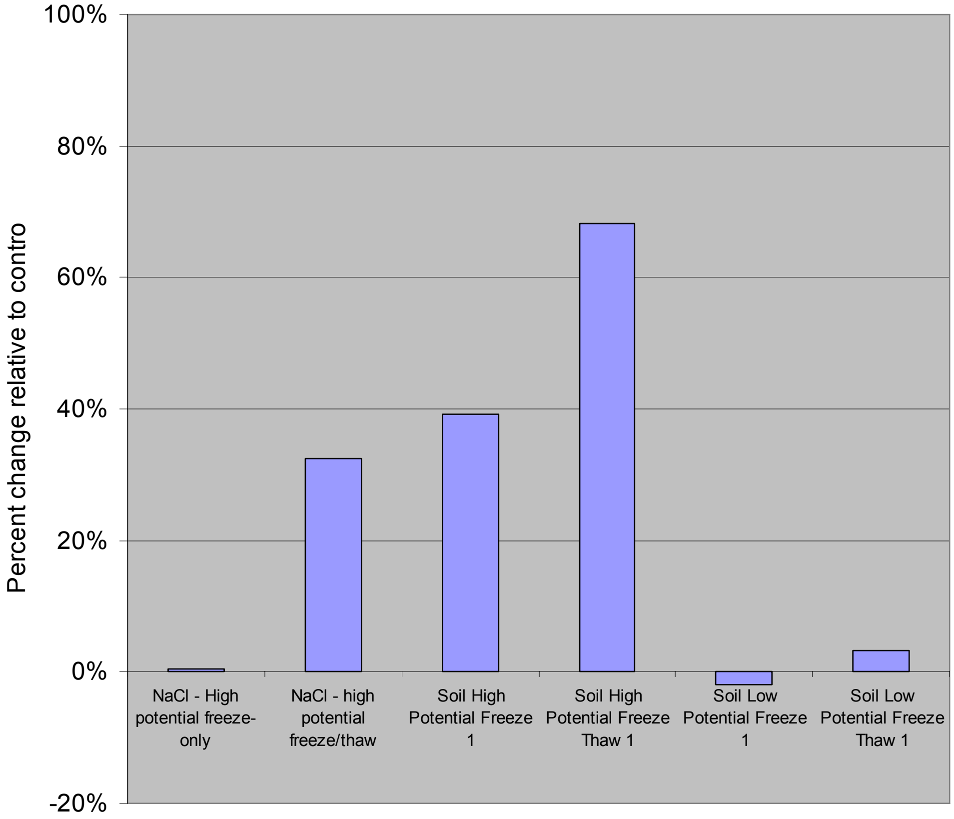

**Figure 9. Cathodic disbondment – relative effects of temperature and polarization (compared to room temperature tests).**