Pacific Gas and Electric Company

EPIC Final Report

Program	***Electric Program Investment Charge (EPIC)***
Project	***EPIC 1.09B/1.10B – Test New Remote Monitoring and Control Systems for T&D Assets / Demonstrate New Strategies and Technologies to Improve the Efficacy of Existing Maintenance and Replacement Programs***
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Table of Acronyms

CBM	Condition Based Maintenance
CPUC	California Public Utilities Commission
EPIC	Electric Program Investment Charge
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition

1.0 Executive Summary

Pacific Gas and Electric Company's (PG&E) Electric Program Investment Charge (EPIC) Project 1.09B / 1.10B *Network Condition Based Maintenance* project successfully demonstrated methods of evaluating and extending the longevity, resiliency and data integrity of Supervisory Control and Data Acquisition (SCADA) condition monitoring components over time.

SCADA and monitoring systems are widely used in power infrastructure, including transmission, distribution, and distribution network systems. PG&E uses SCADA and monitoring sensors (such as oil temperature, oil pressure, oil level, and ambient temperature sensors) to determine the condition and proactively maintain its distribution network systems. Various monitoring sensors are installed on the network transformers to collect data that complements the data in the Condition Based Maintenance (CBM) system in an effort to assess real-time equipment condition. Such proactive maintenance can enable the identification and repair of issues prior to the failure of an asset or an unplanned outage.

Real time monitoring of the system is critical in areas such as the financial district of San Francisco and in downtown Oakland, as equipment is often in the streets and sidewalks. Any distribution network equipment failure could therefore have a significant impact on public safety and customers such as City Hall, hotels, businesses, data centers, financial institutes, convention centers, high-rise residential, shopping centers, BART stations, etc.

Real-time condition monitoring of this system provides a key input to support proactive mitigation of equipment-related issues. However, monitoring components installed in an underground environment are subject to harsh conditions such as moisture, corrosion and high temperatures, which could potentially affect the resiliency and accuracy of the monitoring devices. PG&E has found evidence of corrosion on some of the older SCADA equipment in the vaults in San Francisco, likely due to local weather conditions. PG&E engineers have also found some data integrity issues, such as intermittent loss of data (connectivity) and sustained loss of data (failed communication component). When these issues occur, readings may drop significantly out of range periodically on different pieces of equipment that do not have any known issues, or the data may remain completely static for a reading such as oil temperature that should have natural fluctuations throughout the day.

PG&E has already installed CBM sensors and the associated monitoring system to approximately 40 percent of the full planned deployment which will cover the San Francisco and Oakland network. Evaluation of equipment robustness and potential lifecycle extension techniques can better position PG&E for reliable operations and future deployments.

Objectives and Scope

In order to address the issues and opportunities outlined above, the project accomplished the following objectives:

- **Accelerated Lifecycle Testing:** Conduct accelerated lifecycle testing to establish a baseline for the robustness of SCADA condition monitoring equipment exposed to underground vault environmental conditions over an elongated period of time, and evaluate potential failure points within the components.

- **Demonstration of Life Extension Approaches:** Identify and demonstrate what technologies and improvements, if any, could be applied to increase life expectancy of components and reduce production and maintenance costs.
- **Evaluation of Data Integrity:** Identify opportunities to enhance the efficacy of maintenance and replacement programs by determining methods to enhance the data integrity of the condition monitoring information being collected by the SCADA system.

A laboratory demonstration was performed to simulate an accelerated lifetime representing approximately 30 years of equipment life. This testing was performed by placing the test equipment inside an environmental chamber and exposing the devices to high humidity and cycling temperatures. Approximately 2,500 hours of usable data comprising more than 1.7 million data points were collected during several months of testing. Testing included running the SCADA equipment under normal operating conditions within an environmental chamber leveraging multiple temperature and humidity cycles, averaging with approximately 90 percent relative humidity with cycles of temperature between 25°C up to maximum 75°C.

Several types of SCADA condition monitoring equipment were subjected to this accelerated lifecycle testing, both at the system level (data concentrator units and remote terminal units) and component level (ambient temperature sensors). The project then demonstrated re-torqueing of the connectors as a life-extension approach, as well as the impact of mechanical stress on the connectors that can occur upon installation.

Listed below are descriptions of the equipment tested. A failure by these components could potentially contribute to limitations in PG&E's ability to effectively and proactively monitor and control the local system.

SCADA System Components

1. **Remote Terminal Unit (RTU):** Collects sensor information from the equipment, such as oil level, oil temperature, oil pressure, vault temperature and water level and communicates this information to a Data Concentrator Unit.
2. **Data Concentrator Unit:** Collects data from the remote terminal unit(s) and transmits this data to the SCADA software system.

Targeted Individual System Components

1. **Ambient Temperature Sensors:** Primarily used for ambient temperature measurement inside the vault and remote terminal unit. These sensors provide information to proactively mitigate vault equipment from overheating, a condition which could contribute to deterioration and failure.
2. **Screw Terminal Type Connectors:** These connectors provide power and signals between the RTU and the data concentrator. The demonstration was based on monitoring the connector resistance that could increase as a result of the corrosion material build-up at the electrical contacts while exposed to high humidity and temperature variations. This condition refers to the resistance to current flow that can cause voltage drops in the system and loss of communications.

Additionally, in order to identify opportunities to enhance the efficacy of maintenance and replacement programs, the project conducted an analysis of the data integrity of condition monitoring information being collected by the SCADA system. The project analyzed 365 days worth of historical data from the oil sensors in relation to physical placement of the sensors, precipitation, day of the week, and the impact of remote resets.

Key Project Learnings and Next Steps

Overall, EPIC 1.09B/1.10B successfully evaluated and demonstrated appropriate maintenance over the life of the system, equipment resiliency and ways to extend the longevity and integrity of the system. There were several key learnings and next steps from the primary work streams within the project that could potentially support decision making and enable future improvements for this equipment.

- **Learning – Connector Type (Pinned or Bare Wire) Impacts Resiliency:** Lifecycle testing of the connectors provided evidence that connections installed at the SCADA system are reliable and resilient. Exposure of electrical connectors to high temperature and humidity environments did not cause failure over three months of accelerated lifecycle testing. This length of accelerated life testing approximated 30 years of real-world conditions. However, lifecycle testing did show a drop in connection strength after initial exposure to a high humidity environment. Bare wire connections were demonstrated to show a bigger drop in connection strength than pinned connections.

  Next Step – Explore Pin Wire Connections for Improved Resiliency: PG&E will explore leveraging pinned wire for the screw terminal type connectors in new underground vault installations for greater connection strength over time. This improvement in resiliency will potentially extend the life of condition monitoring equipment and support the robustness of the condition-based maintenance system. While many connections are currently bare wire, next steps will focus on new installations as opposed to retrofit as a cost-effective approach.

- **Learning – Re-Torqueing Connections Positively Impacts Resiliency:** Re-torqueing the connectors one-time soon after the initial installation was demonstrated to be effective in maintaining good connectivity for the remaining duration of testing.

  Next Step – Explore Processes to Potentially Add a Re-Torque of Connections After Installation: As a result of these learnings, PG&E will review current maintenance requirements post-installation, including potentially building in re-torqueing of the connections during the first few years of installation into maintenance plans.

- **Learning – Weight or Pull Has No Significant Impact on Connector Resiliency:** The application of weight to simulate inadvertent pull or mechanical stress on the connectors was also shown to have a minor impact on resistance, but did not significantly impact the performance of equipment. As a result of these findings, no next step will be explored at this time with regards to inadvertent weight or pull on connectors at installation or repair.

- **The Resiliency of Ambient Temperature Sensors Is Dependent Upon Location:** The project identified the failure of two ambient temperature sensors included in the demonstration during accelerated lifecycle testing. Both of these sensors were located outside of the RTU and data concentrator units, exposed directly to the elements of the test chamber.

  Next Step – Explore More Resilient Ambient Temperature Sensors for New Installations: While testing revealed the failure of two sensors, these devices can be monitored remotely, alerting the utility when replacement is needed. Temperature sensors with greater resistance to ambient temperature and humidity are available but they are more costly. With these considerations, there is minimal economic benefit to reducing failures through the replacement of previous sensors with more costly sensors with lower failure rates. However, due to these results, PG&E will explore more resilient components for new installations.

- **Learning – The SCADA RTUs Have Opportunities to Become More Robust:** The serial communication between the RTU box and the data concentrator was lost twice during testing. Testing indicated that it could be due to a resistive short as a result of moisture condensation and contamination at the connectors of the communication lines.

  Next Step – Enhance resiliency of the SCADA RTU: The communication link between the data concentrator and RTU is critical for receiving the data from the condition monitoring sensors. PG&E will be working with the manufacturer to improve the reliability of this component.

- **Learning – Location, Data Timing, Remote Resets, and Precipitation All Impact Oil Sensor Data Integrity:** Statistical analysis of 365 days of actual historical data illustrated that oil pressure and level sensors for the ground switch chamber have significantly higher rates of false readings than other sensors. Further analysis illustrates that this may be attributable to sensor connection placement, as sensor connections made in the RTU expansion board were more likely to have a false reading. Additionally, a correlation was found to certain days of the week with significantly higher rates of false readings, which may be attributed to a change of vault temperature from weekend to weekdays. False oil temperature readings were found to be slightly correlated to precipitation. However, the overall number of bad temperature readings compared to level and pressure readings is small (approximately 100 bad temperature data points versus more than approximately 94,000 bad oil level and 82,000 bad pressure data points in 365 days).

  Next Step – Enhance Condition Monitoring Data Integrity: PG&E is working with the manufacturer of the RTU expansion board to improve the reliability. This includes further investigation of the false readings and correlation to days of the week. Currently, processes to discover and assess data issues are manual. As such, PG&E will also explore the development of automated data integrity tools for monitoring, alerting and quality checking the sensor data recorded by the PG&E SCADA system.

Conclusion

This project has captured key learnings that can be leveraged by other utilities and industry members to address the longevity of electrical connectors, sensors, and SCADA systems installed inside underground electrical vaults of distribution networks.

Overall, the system is well designed and the components used are generally compatible with the environment where they are installed. The SCADA and associated monitoring system can effectively be used to remotely gather real-time data from within the electrical vaults. Sensors and connectors used within the underground vaults of the distribution system generally showed resistance to high temperature and humidity environments. Bad data points can be monitored alerting the utility about on-going issues or failures that need to be addressed, including failed sensors. The system can be remotely reset to prevent bad data measurements from the oil level and oil pressure sensors connected to the expansion board of the data concentrator enclosure.

Although PG&E's system is robust, this project identified areas of improvement that PG&E will explore as potential next steps, including:

- Adding re-torqueing of connectors during the first few years post-installation to maintenance plans for improved equipment resiliency
- Leveraging more robust ambient temperature sensors and more reliable RTU expansion board for future installations
- Developing automated monitoring tools for improved understanding of data integrity

This project has confirmed the overall strength of the monitoring and communication systems currently installed across the distribution network and demonstrated methods for improving the life and data integrity of its components. The results and learnings from EPIC 1.09B/1.10B will support a robust condition-based maintenance program by enhancing equipment resiliency and data integrity.

2.0 Introduction

This report documents the EPIC 1.09B/1.10B – Network Condition Based Maintenance project achievements, highlights key learnings from the project that have industry-wide value, and identifies future opportunities for PG&E to leverage this project.

The California Public Utilities Commission (CPUC) passed two decisions that established the basis for this pilot program. The CPUC initially issued D. 11-12-035, *Decision Establishing Interim Research, Development and Demonstrations and Renewables Program Funding Level*[1], which established the Electric Program Investment Charge (EPIC) on December 15, 2011. Subsequently, on May 24, 2012, the CPUC issued D. 12-05-037, *Phase 2 Decision Establishing Purposes and Governance for Electric Program Investment Charge and Establishing Funding Collections for 2013-2020*[2], which authorized funding in the areas of applied research and development, technology demonstration and deployment (TD&D), and market facilitation. In this later decision, CPUC defined TD&D as "the installation and operation of pre-commercial technologies or strategies at a scale sufficiently large and in conditions sufficiently reflective of anticipated actual operating environments to enable appraisal of the operational and performance characteristics and the financial risks associated with a given technology."[3]

The decision also required the EPIC Program Administrators[4] to submit Triennial Investment Plans to cover three-year funding cycles for 2012-2014, 2015-2017, and 2018-2020. On November 1, 2012, in A.12-11-003, PG&E filed its first triennial Electric Program Investment Charge (EPIC) Application at the CPUC, requesting $49,328,000 including funding for 26 Technology Demonstration and Deployment Projects. On November 14, 2013, in D.13-11-025, the CPUC approved PG&E's EPIC plan, including $49,328,000 for this program category. Pursuant to PG&E's approved EPIC triennial plan, PG&E initiated, planned and implemented the following project: 1.09B / 1.10B, Network Conditioned-Based

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[1] http://docs.cpuc.ca.gov/PublishedDocs/WORD_PDF/FINAL_DECISION/156050.PDF.

[2] http://docs.cpuc.ca.gov/PublishedDocs/WORD_PDF/FINAL_DECISION/167664.PDF.

[3] Decision 12-05-037 pg. 37.

[4] Pacific Gas & Electric (PG&E), San Diego Gas & Electric (SDG&E), Southern California Edison (SCE), and the California Energy Commission (CEC).

Maintenance. Through the annual reporting process, PG&E kept CPUC staff and stakeholder informed on the progress of the project. The following is PG&E's final report on this project.

3.0 Project Overview

This section summarizes the industry gap addressed by the project, the project's objectives, the scope of work and the major tasks and associated deliverables.

3.1 Issue Addressed

Supervisory Control and Data Acquisition (SCADA) and monitoring systems are widely used in power infrastructure, including transmission, distribution, and distribution network systems. PG&E uses SCADA and monitoring sensors (such as oil temperature, oil pressure, oil level, and ambient temperature sensors) to determine the condition and proactively maintain its distribution network systems. Various monitoring sensors are installed on the network transformers to collect data that complements the data in the Condition Based Maintenance (CBM) system in an effort to assess real-time equipment condition. Such proactive maintenance can enable the identification and repair of issues prior to the failure of an asset or an unplanned outage.

Real time monitoring of the system is critical in areas such as the financial district of San Francisco and in downtown Oakland, as equipment is often in the streets and sidewalks. Any distribution network equipment failure could therefore have a significant impact on public safety and customers such as City Hall, hotels, businesses, data centers, financial institutes, convention centers, high-rise residential, shopping centers, BART stations, etc.

Real-time condition monitoring of this system provides a key input to support proactive mitigation of equipment-related issues. However, monitoring components installed in an underground environment are subject to harsh conditions such as moisture, corrosion and high temperatures, which could potentially affect the resiliency and accuracy of the monitoring devices. PG&E has found evidence of corrosion on some of the older SCADA equipment in the vaults in San Francisco, likely due to local weather conditions. PG&E engineers have also found some data integrity issues, such as intermittent loss of data (connectivity) and sustained loss of data (failed communication component). When these issues occur, readings may drop significantly out of range periodically on different pieces of equipment that do not have any known issues, or the data may remain completely static for a reading such as oil temperature that should have natural fluctuations throughout the day.

PG&E has already installed CBM sensors and the associated monitoring system to approximately 40% of the full planned deployment which will cover the San Francisco and Oakland network. Evaluation of equipment robustness and potential lifecycle extension techniques can better position PG&E for reliable operations and future deployments.

3.2 Project Objective

EPIC 1.09B/1.10B accomplished the following key objectives:

- **Accelerated Lifecycle Testing:** Conduct accelerated lifecycle testing to establish a baseline for the robustness of SCADA condition monitoring equipment exposed to underground vault environmental conditions over an elongated period of time, and evaluate potential failure points within the components.

- **Demonstration of Life Extension Approaches:** Identify and demonstrate what technologies and improvements, if any, could be applied to increase life expectancy of components and reduce production and maintenance costs.
- **Evaluation of Data Integrity:** Identify opportunities to enhance the efficacy of maintenance and replacement programs by determining methods to enhance the data integrity of the condition monitoring information being collected by the SCADA system.

3.3 Scope of Work

A laboratory demonstration was performed to simulate an accelerated lifetime representing approximately 30 years of equipment life. This testing was performed by placing the test equipment inside an environmental chamber and exposing them to high humidity and cycling temperatures. Approximately 2500 hours of usable data comprising over 1.7 million data points were collected during several months of testing. Testing included running the SCADA equipment under normal operating conditions within an environmental chamber leveraging multiple temperature and humidity cycles, averaging with approximately 90% relative humidity with cycles of temperature between 25°C up to maximum 75°C.

Several types of SCADA condition monitoring equipment were subjected to accelerated lifecycle testing, both at the system level (data concentrator units and remote terminal units) and component level (ambient temperature sensors). The project then demonstrated re-torqueing of the connectors as a life extension approach, as well as the impact of mechanical stress on the connectors that can occur upon installation.

Additionally, in order to identify opportunities to enhance the efficacy of maintenance and replacement programs, the project conducted a review of the data integrity of condition monitoring information being collected by the SCADA system for oil sensors

3.4 Description of System Components

On a local distribution vault system level, multiple data points are collected from condition monitoring sensors by a local remote terminal unit (RTU), which then communicates this information to a local data concentrator unit via serial communication line. Live sensor data is then reported through the data concentrator and is recorded and stored in the SCADA database.

Several condition monitoring sensors are deployed on underground distribution equipment such as transformers and switches. Input from these sensors can be accessed through the RTU and the data concentrator web interface. Some of the sensor inputs, such as the ambient temperature and water level (inside the vault), are accessed through dedicated transducers inside the RTU box. Other sensors inputs are accessed through the data concentrator. Oil temperature, oil level, and oil pressure of transformer tanks and oil-filled switches are among the sensor inputs that are accessed through the data concentrator. These are the main sensor inputs that provide information about the operating condition of major equipment, such as the transformers and network switches inside the vault.

The schematic in Figure 3-1 below highlights the typical local connections in this type of system:

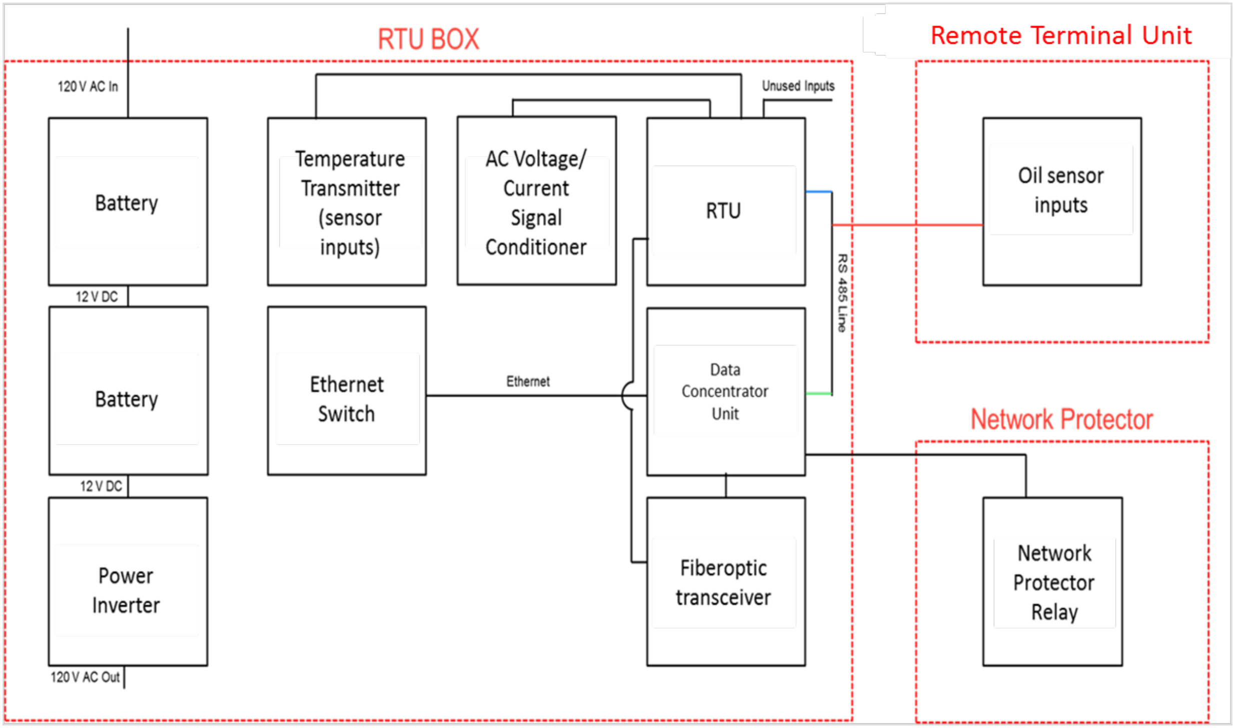

Figure 3-1 Local SCADA system components schematic

Listed below is a description of the equipment included in this demonstration. A failure by these components could potentially contribute to limitations in PG&E's ability to effectively and proactively monitor and control the local system.

Ambient temperature sensors were included in accelerated lifecycle testing, while oil and water level sensors were not. Sensors excluded from the demonstration testing were either already considered robust pieces of equipment or were housed in an area of the vault that is sealed from potential environmental impacts, thus limiting the potential value of demonstrating their resiliency.

SCADA System Components

- **Remote Terminal Unit:** Collects sensor information from the equipment, such as oil level, oil temperature, oil pressure, vault temperature and water level and communicates this information to a Data Concentrator Unit.

- **Data Concentrator Unit:** Collects data from the remote terminal unit(s) and transmits this data to the SCADA software system.

Targeted Individual System Components

- **Ambient Temperature Sensors:** Primarily used for ambient temperature measurement inside the vault and remote terminal unit. These sensors provide information to proactively mitigate vault equipment from overheating, a condition which could contribute to deterioration and failure.

These sensors were included in the accelerated lifecycle testing for this project. Further technical description of ambient temperature sensors as well as oil temperature sensors can be found in Appendix A.

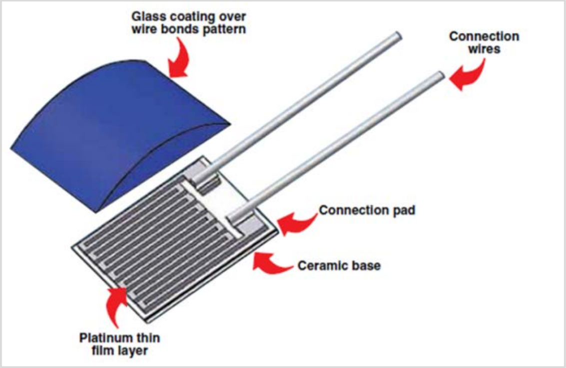

Figure 3-2 Schematic diagram of an ambient temperature sensor

- **Screw Terminal Type Connectors:** These connectors provide power and signals between the RTU and the data concentrator. The demonstration was based on monitoring the connector resistance that could increase as a result of the corrosion material build-up at the electrical contacts while exposed to high humidity and temperature variations. This condition refers to the resistance to current flow that can cause voltage drops in the system and loss of communications.

- **Oil Sensors:** Primarily used for oil level, pressure and temperature measurements inside the transformer and power switch tanks that are filled with electrical insulating oil. Maintenance of oil level is critical to preventing the transformer from overheating, and maintenance of oil pressure is critical to ensuring there are no leaks in the transformer tank that could cause moisture contamination.

  Transformers and other oil-filled equipment are sealed from the outside environment. This is because the electrical insulating oil can lose its insulation properties if it comes into contact with the outside environment due to moisture absorption. Therefore, the oil sensor within different transformers will be in the relatively same conditions regardless of any differences in the environments in which different transformers are located. The life of an oil temperature sensor that is used inside a transformer in an underground vault is not expected to be significantly different than that which is used in a transformer above the ground. Therefore, no life cycle testing was done on this type of sensor. However, due to PG&E operations reports of false readings, these sensors were analyzed for data integrity.

4.0 Major Tasks

EPIC 1.09B/1.10B completed the following major tasks, each described in the subsections below:

1. Accelerated lifecycle demonstration
   a. Condition monitoring sensors (ambient temperature sensors)
   b. SCADA equipment (Data concentrators and RTUs)
2. Evaluation and demonstration of life extension approaches (Connectors)
3. Condition monitoring data integrity analysis

4.1 Accelerated Lifecycle Demonstration

A laboratory demonstration was performed to simulate an accelerated lifetime to establish a baseline of performance representing approximately 30 years of equipment life. This testing was performed by placing the test equipment inside an environmental chamber and exposing them to high humidity and cycling temperatures. Approximately 2500 hours of usable data comprising over 1.7 million data points were collected during several months of testing. Testing included running the SCADA equipment under normal operating conditions within an environmental chamber leveraging multiple temperature and humidity cycles, averaging with approximately 90% relative humidity with cycles of temperature between 25°C up to maximum 75°C. See Appendix B for further details of relevant standards related to environmental testing.

Different temperature profiles were developed and leveraged during this demonstration. See Appendix C for graphical depictions of the temperature profiles described below:

- Profile 0: Temperature variations of 35-55°C and average RH less than 90%; 10 minutes ramp to high temperature, 1 hour at the high temperature, 10 minutes cool down to low temperature, and 1 hour at the low temperature.

- Profile 1: Temperature variations of 20-75°C and average 90% RH profile; 2.5-hour ramp to high temperature, 3 hours at the high temperature, 2.5-hour cooldown to low temperature, and 0 hours at the low temperature.

- Profile 2: Temperature variations of 25-65°C and average 90% RH profile; 2.5-hour ramp to high temperature, 3 hours at the high temperature, 2.5-hour cooldown to low temperature, and 0 hours at the low temperature.

- Profile 3: Temperature variations of 25-65°C and average 90% RH profile; 1.5-hour rise to high temperature and 1.5-hour cooldown to low temperature, with no dwelling time at the high or low temperatures.

- Profile 4: Temperature variations of 25-75°C and average 90% RH profile; 1.5-hour ramp to high temperature, 3 hours at the high temperature, 1.5-hour cooldown to low temperature, 0 hours at the low temperature.

- Profile 5: Temperature variations of 25-65°C and average 90% RH profile; 1.5-hour ramp up, 3 hours at high, 1.5-hour cooldown, and 0 hours at low.

Table 4-1 illustrates the total number of hours and cycles conducted for each environmental profile.

No	Environmental profile	Profile summary	Total hours at the profile	No of cycles at the profile
0	Profile 0	35-55°C. 10 minutes ramp, 1 hour at high, 10 minutes fall, 1 hour at low	720	309
1	Profile 1	20-75°C. 2.5-hr ramp, 3 hrs at high, 2.5-hr fall	2261	283
2	Profile 2	25-65°C. 2.5-hr ramp, 3 hrs at high, 2.5-hr fall	227	28
3	Profile 3	25-65°C. 1.5-hr ramp, 0 hrs at high, 1.5-hr fall	662	221
4	Profile 4	25-75°C. 1.5-hr ramp, 0 hrs at high, 1.5-hr fall	1253	418
5	Profile 5	25-65°C. 1.5-hr ramp, 3 hrs at high, 1.5-hr fall	713	119

Table 4-1 Accelerated Lifecycle Testing Cycle Summary

Figure 4-1 depicts the test set up leveraged for accelerated lifecycle testing.

Figure 4-1 Environmental chambers used for accelerated lifecycle testing

4.1.1 Condition Monitoring Sensors

EPIC 1.09B/1.10B demonstrated accelerated lifecycle testing of ambient temperature sensors. Four ambient temperature sensors were subjected to multiple cycles in the environmental chamber. Sensors were placed outside the data concentrator and RTU box, and also inside the data concentrator and RTU box, in order to determine if location of the sensor would impact resiliency of the device to environmental conditions over time.

4.1.2 SCADA Equipment

The project team operated a RTU box and a data concentrator unit within the environmental chamber. Wiring connections were made between the two units inside the environmental chamber through conduits similar to actual PG&E installations. Connection was also made between the RTU box and a network relay outside the environmental chamber. The state of the network relay switch was reported to the data concentrator within the RTU box via a serial connection. A data concentrator web interface was accessed through a secure Local Area Network (LAN) and the webpage was periodically recorded for any sign of malfunction in the system or the sensor readings. Approximately 1400 cycles of temperature with different profiles were applied during the environmental chamber testing.

Figure 4-2 depicts the set up leveraged for SCADA equipment accelerated lifecycle testing.

Figure 4-2 SCADA Equipment Test Set Up

4.2 Evaluation and Demonstration of Life Extension Approaches

In this task, potential approaches to extending the life of the SCADA monitoring system were identified and demonstrated. Moisture and temperature are known primary environmental factors that can cause failure of electric components[5]. As such, the project demonstrated and evaluated potential human factors, such as inadvertent pull or mechanical stress on conductors during maintenance/installation or improper torques of connections, and their impact on equipment resilience over time

Four screw terminal type connectors in exemplar condition from five different manufacturers were selected for this testing. From the four exemplar connectors that were selected, two of the connectors had pinned wire connections and two of them had bare wire connections. Of the two connectors with the bare wire or pinned wire connections of each manufacturer, one connector had connections with insulating grease and one connector had connections without grease.

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[5] "Electronic Failure Analysis Handbook," Perry L. Martin, McGraw-Hill, 1999, P.1.4.

No. of Connectors by Characteristic	Grease	No Grease
Pinned	1 connector	1 connector
Wire	1 connector	1 connector

The following test protocol was developed to investigate the failure mechanism of the connectors. This failure mechanism is expected to be primarily due to corrosion buildup at the electrical contacts during testing.

1. Identify different manufacturers of the connector type and acquire exemplars of each connector.
2. Attach wires to the connectors using two different methods, bare wire and pinned wire connection methods. Use an equal number of the exemplars from each manufacturer for each wire connection method. Use stranded wires of the same type that is used in the RTU box and the data concentrator units.
3. Mount all the connectors on a test fixture.
4. Apply up to 2A DC current to the connectors through each wire connection. Instrument the connectors to measure the voltage drop across each connector.
5. Place the test fixture in an environmental chamber with high humidity and cycling temperatures.
6. Periodically measure and record the voltage drop across each connector using a calibrated data logger capable of measuring low DC voltages. The total DC current supplied by the external power supply was also monitored and recorded at the same time as the connector voltages; therefore, the total connector resistance could be calculated and recorded periodically.

Figure 4-3 depicts the test set up for connector testing, and Figure 4-4 depicts the bare and pinned wire connection types.

Figure 4-3 Test Set Up For Connectors

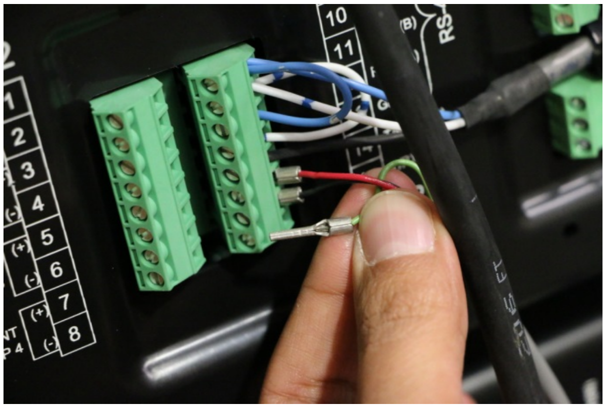


Figure 4-4 Two Different Wire Connection Methods.

- **Weight Testing on Connectors:** This test was designed to simulate inadvertent pull or mechanical stress on the wires during the maintenance or installation of adjacent components and evaluate if such stress could cause issues with the electrical connection. Weights were added at each wire between two connections within the same connector or between two adjacent connectors (approximately 1 pound of force at each connection). Weights were added approximately after approximately 500 cycles of temperature in the environmental chamber.

- **Torque Testing on Connectors:** This test was design to demonstrate influence of connector tightening on resiliency of the connection over time. At three separate instances during the environmental testing (at 120, 260 and 880 cycles), all the connector torques were checked, re-torqued to the original torque value, and the amount of the lost torque value was recorded.

4.3 Condition Monitoring Data Integrity Analysis

Leveraging accurate and precise data from the condition monitoring sensors is important for an effective maintenance and replacement program. System alarms are associated with the sensor inputs, including the oil temperature, oil level, and oil pressure sensors. Distribution operators have provided feedback that they are receiving false alarms related to the oil sensors. As such, a statistical analysis was performed on the oil temperature, oil pressure and oil level data as reported through the data concentrator. The project leveraged a full year of historical data from the sensors to assess the performance of the sensors under normal operating conditions.

The main focus of the statistical analysis was on the following data:

1. 365 days of sensor readings from 849 oil sensors
2. Queried for recordings with extreme low values (false readings):
    a. Level below -800
    b. Pressure below -800
    c. Temperature below -10°C

The analysis targeted the evaluation of four potential influences on oil sensor data integrity:

1. **Impact of sensor location:** Oil sensors are located on ground switch chambers, main tanks and primary chambers. Temperature sensors data is taken to the main board of the data concentrator units, while oil level and pressure data is taken to an “expansion board” located

off of the main data concentrator board. As such, the project compared false readings to the type of sensor as well as the location of the sensor itself and where its data is concentrated.

2. **Remote reset:** It had been reported that it appeared false readings via the SCADA system could potentially be corrected by remotely resetting the equipment. As such, the project compared false readings with timing of remote resetting activities.
3. **Weather conditions:** The project compared monthly precipitation with total monthly false readings from oil sensors.
4. **Day of the week:** The project compared the number of false readings against the day of the week for patterns.

5.0 Learnings and Next Steps

5.1 Accelerated Lifecycle Testing

5.1.1 Condition Monitoring Sensor Testing Results

Demonstrating and evaluating conditions under which condition monitoring sensors may fail supports a robust condition based maintenance program. These sensors are leveraged to proactively prevent equipment from overheating through preventative maintenance. Their failure could potentially lead to increased maintenance costs of both the sensor and major equipment.

Overall, ambient temperature sensors were found to be relatively resilient to environmental conditions during testing. The sensors located inside either an RTU or data concentrator box were less likely to experience failures and corrosion than those located outside the boxes. Ambient temperature sensors located outside these boxes failed twice during testing, both failures occurring after approximately 1200 cycles in the environmental chamber.

Table 8-1 below illustrates the results of accelerated lifecycle testing of the ambient temperature sensor based upon different sensor placements:

Sensor Location	Result
Inside the RTU box	Passed all cycles of testing without equipment failure. No obvious evidence of corrosion, likely attributable to the fact that they were not directly exposed to the high humidity of the test chamber. (Figure 5-2)
Inside the data concentrator	No equipment failure, however partial delamination was observed (loss of mechanical toughness due to separation of material layers). Likely attributable to partial exposure of the sensor to the elements through the potting material on the sensor (sealant to exclude moisture and corrosive elements). (Figure 5-3)
Outside the RTU box	Experienced one equipment failure of one sensor after approximately 1200 cycles in the environmental chamber, mostly likely attributable to direct exposure to the humidity of the test chamber. There was evidence of corrosion visible on the sensor. Also visible was discoloration and irregularities in the potting material that covers the sensing element. (Figure 5-4)
Outside the data concentrator	Experienced one equipment failure of one sensor after approximately 1200 cycles in the environmental chamber, mostly likely attributable to direct exposure to the humidity of the test chamber. The black potting material on the sensing element of the failed sensor was cracked/ torn and separated from the sensing element. Additionally, there were cracks in the glass coating of the sensing element and possible delamination. (Figure 5-5)

Figure 5-1 Ambient Temperature Sensor Test Results

Figure 5-2 Ambient Temperature Sensor Inside the RTU

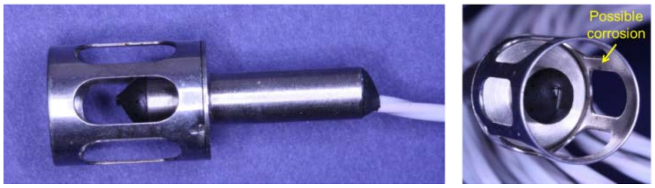


Figure 5-3 Ambient Temperature Sensor Inside the Data Concentrator

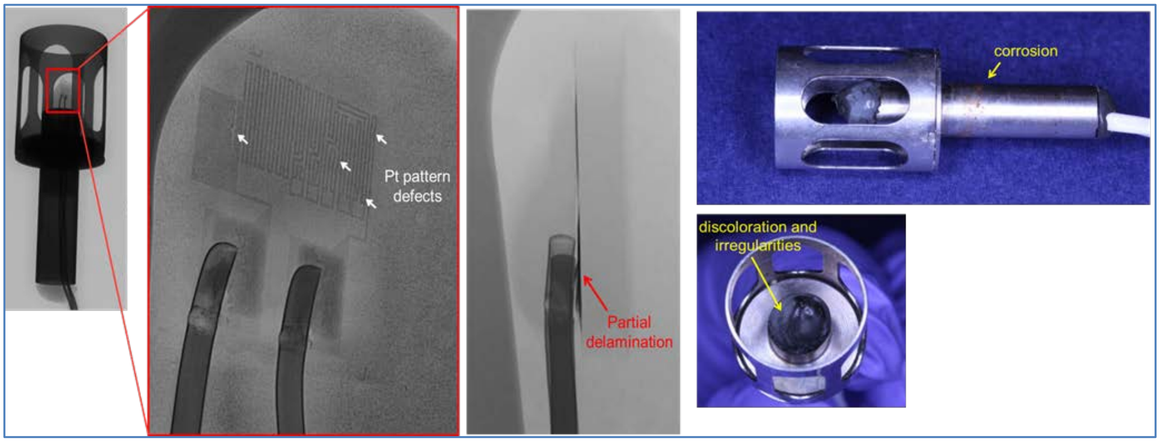


Figure 5-4 Failed Ambient Temperature Sensor Outside the RTU

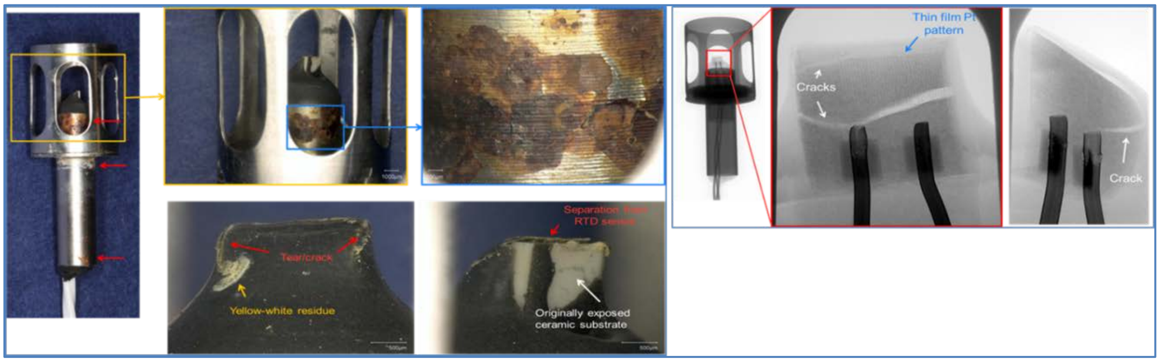


Figure 5-5 Failed Ambient Temperature Sensor Outside the Data Concentrator

While testing revealed the failure of two sensors, these devices can be monitored remotely, alerting the utility when replacement is needed. Temperature sensors with greater resistance to ambient temperature and humidity are available but they are more costly. Due to these considerations, there is minimal economic benefit to reducing failures through the replacement of previous sensors with more costly sensors with lower failure rates. However, PG&E will consider a more resilient component for new installations.

5.1.2 SCADA Equipment Testing Results

Approximately 1400 cycles of temperature with different temperature and humidity profiles were applied during the environmental chamber testing. The serial communication between the RTU box and the data concentrator was lost twice during this time period. The first instance occurred after approximately 416 cycles. The second instance occurred after approximately 1217 cycles in the environmental chamber.

Both times, the signal was restored before the cause of the failure could be determined. Attempts to the recreate the exact same failure, which included introducing localized moisture and the connections of the communication wiring and continuing the test inside the environmental chamber, were unsuccessful.

A series of tests were performed on an RTU box outside the chamber to investigate the possible effects of such a failure mode. The communication cable consisted of three wires that were color coded blue, white and black. The black wire was the ground connection (GND). The blue wire carried the serial communication signal and the white wire was the invert of the blue wire signal. The blue wire signal was designated as the positive (+) signal and the white wire as the negative (-) signal. The negative signal was discovered to be distorted.

Different wires in the serial communication cable were shorted to ground using different resistors simulating resistive connections due to contamination and moisture. It was discovered that the shorting resistance has to be less than 10 ohms before an adverse effect was observed in the communication signals. In order to explore the effect of such a resistive short due to possible moisture intrusion at the wire connections, different wires were electrically shorted together for different periods of times. The effect of the electrical short was then recorded before and after removal of the short. It was discovered the system response to such a failure mode is not only a function of the induced fault (which wires were shorted), but also how long the fault persisted between those lines.

In general, it was discovered that the system was more affected as a result of a short between the white wire (-) to ground. Also, the system was more likely to recover and resume normal communications if the fault was removed quickly after losing communication as a result of the fault. Additionally, resetting was required to restore the system when the communication was lost after removing the fault.

In summary, testing indicated that it could be due to a resistive short as a result of moisture condensation and contamination at the connectors of the communication lines. The communication link between the data concentrator and RTU is critical for receiving the data from the condition monitoring sensors. PG&E will be working with the manufacturer to improve the reliability of this component.

5.2 Evaluation and Demonstration of Life Extension Approaches

The project demonstrated and evaluated potential human factors and their impact on equipment resilience over time, more specifically demonstrating inadvertent pull or mechanical stress on conductors during maintenance/installation as well as torqueing and re-torqueing connections. Extending the life of SCADA equipment could potentially reduce the cost of maintenance and replacement due to reduced equipment failure and issues.

5.2.1 Overall Connector Resiliency

Connectors under test were exposed to cycles in a high temperature, high humidity environment to simulate conditions seen in underground electrical vaults. The testing was performed with all connectors carrying the same electrical current (approximately 2 amperes) and with monitoring the voltage drop across each electrical connection within the connector.

Because the electrical resistance of the connectors is normally low, the voltage drop across each electrical connection is very small (millivolts). However, because the connectors were exposed to high humidity and temperature variations within the environmental testing, the contact resistance increased over time, most likely as a result of the development of corrosion products at the contact surfaces (Figure 5-6).

Some of the connection resistances started from less than 10 milliohms and increased to near 180 milliohms for approximately 2450 hours-worth of data during this test. Although the increase in overall resistance of the connectors is considerable, a connector with 180 milliohm contact resistance is not expected to be problematic for applications such as the ones in the RTU box and the data concentrator. As shown in Figure 5-7, non-pinned connections had greater resistance increases than pinned connections.

Overall, test data on electrical connections showed the development of corrosion due high temperature and humidity levels, but the quality of the electrical connection did not significantly change. Connectors currently in use showed strong performance as accelerated life testing showed no significant difference between all connectors and wire end types under test. Additionally, resistances for each connector type would increase and decrease during the course of the test. This could be as a result of the slow process of corrosion material buildup at the surfaces of the electrical connections and intermittently making and breaking contacts through corrosion products at the surfaces.

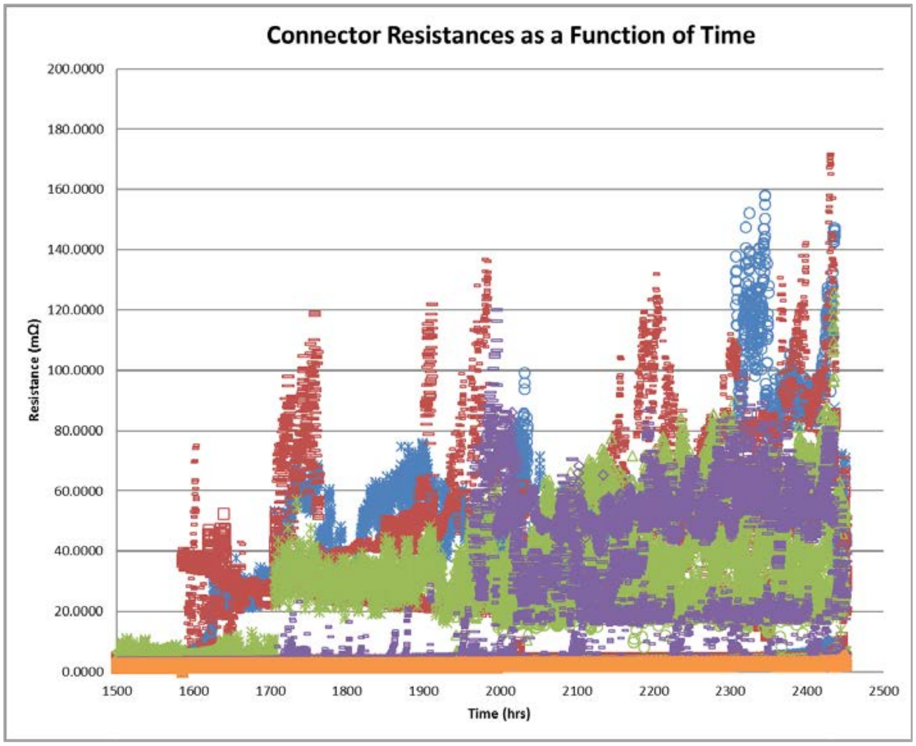


Figure 5-6 Plot of all the connector resistances measured over time

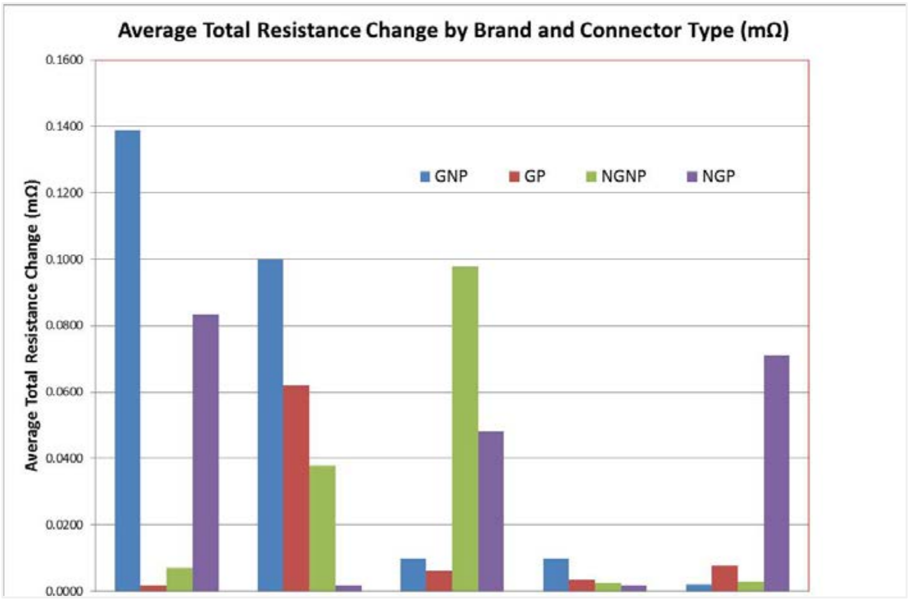


Figure 5-7 Average Total Resistance Change by Connector Type for 5 different manufacturers

5.2.2 Weight Testing

To simulate inadvertent pull or mechanical stress on the wires during the maintenance or installing adjacent components, weights were added at each wire between two connections within the same connector or between two adjacent connectors (approximately 1 pound of force at each connection). This was done to evaluate if such stress could cause issues with the electrical connection. Weights were added approximately after approximately 500 cycles of temperature in the environmental chamber.

The resistance of the connectors slightly increased as a result of the added weight. One of the connector types (no grease, pinned connection) showed a greater increase in resistance than the others, though the total resistance was still low (less than 40 milliohms). However, it was concluded that this was only due to two connectors and was an outlier in the data. Despite the increase in resistance, none of the connectors showed significant decrease in the performance of the electrical connection. A plot of the connector resistances after adding weights is shown in Figure 5-8.

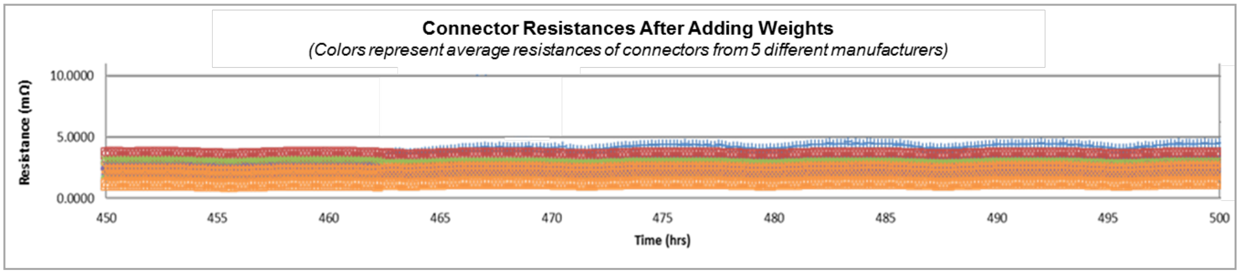


Figure 5-8 Connector Resistances After Adding Weights

5.2.3 Torque Testing

At three separate instances during the environmental testing, all the connector torques were checked, re-torqued to the original torque value, and the amount of the lost torque value was recorded. At approximately 120 and again at 260 cycles into the test, all connectors were re-torqued and the average difference in original torque for each group of connectors was measured.

At 120 and 260 cycles, it was discovered that all of the connectors had lost their torque to some degree, with the highest observed loss of torque value being from the connector with grease and bare wire (no pin). At 880 cycles, the loss of torque was demonstrated as lower than the first two occasions of torqueing back the connectors. Also, pinned connections appear to maintain torque better than wires. This may be due to the fact that pins maintain their shape while torque is applied. Overall, connectors were shown to lose torque after initial exposure to environmental conditions of the vault.

Table 5-1 illustrates the difference in torque value in ounce-inch after approximately 120 cycles into the test with high humidity and temperature cycling for various manufacturers and connection types.

120 Cycles	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5
No Grease, No Pin (NG NP)	-0.17	-0.5	-0.67	-0.83	-1.83
Greased, No Pin (G NP)	-0.67	-1.5	-3.5	-1.67	-1.33
No Grease, Pinned (NG P)	0	0	-0.5	0	-0.17
Greased, Pinned (G P)	0	-0.17	0	0	-0.17

Table 5-1 Connector Torque Differences After 120 Cycles

Table 5-2 illustrates the difference in torque value in ounce-inch after approximately 260 cycles into the test with high humidity and temperature cycling for various manufacturers and connection types.

260 Cycles	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5
No Grease, No Pin (NG NP)	0	-2.33	-3.17	-1	-2.33
Greased, No Pin (G NP)	-0.33	-2.83	-3.5	-2.83	-1.33
No Grease, Pinned (NG P)	-0.33	-0.67	-0.33	-0.67	-0.17
Greased, Pinned (G P)	-0.17	0	-0.83	-0.67	0

Table 5-2 Connector Torque Differences After 260 Cycles

Table 5-3 illustrates the difference in torque value in ounce-inch after approximately 260 cycles into the test with high humidity and temperature cycling for various manufacturers and connection types.

880 Cycles	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5
No Grease, No Pin (NG NP)	0	-0.33	-0.67	-0.17	-0.33
Greased, No Pin (G NP)	0	-0.67	-0.5	-1	-0.83
No Grease, Pinned (NG P)	0	0	0	-0.17	-0.5
Greased, Pinned (G P)	-0. 33	0	-0.17	-0.67	-0.17

Table 5-3 Connector Torque Differences After 880 Cycles

5.3 Condition Monitoring Data Integrity Review Results

Leveraging accurate and precise data from the condition monitoring sensors is important for an effective maintenance and replacement program. Condition based maintenance enables a more proactive approach to management of assets to prevent a potentially costly major failure. This analysis targeted the evaluation of four potential influences on oil sensor data integrity:

1. **Impact of Sensor Location:** Oil sensors are located on ground switch chambers, main tanks and primary chambers. Temperature sensors data is taken to the main board of the data concentrator units, while oil level and pressure data is taken to an “expansion board” located off of the main data concentrator board. As such, the project compared false readings to the type of sensor as well as the location of the sensor itself and where its data is concentrated.

   Result: Oil pressure and level sensors have significantly higher rates of false readings than oil temperature sensors. This may be attributable to sensor connection placement, as sensor connections made in the data concentrator expansion board (from the ground switch) were more likely to have a false reading.

   Figure 5-9 illustrates that false readings were occurring significantly more regularly from the ground switch chambers than main tank or primary chamber. Additionally, Figure 5-10 illustrates that most of these false readings are associated with the oil pressure sensors, which provide data to the data concentrator “extension board” instead of to the main board.

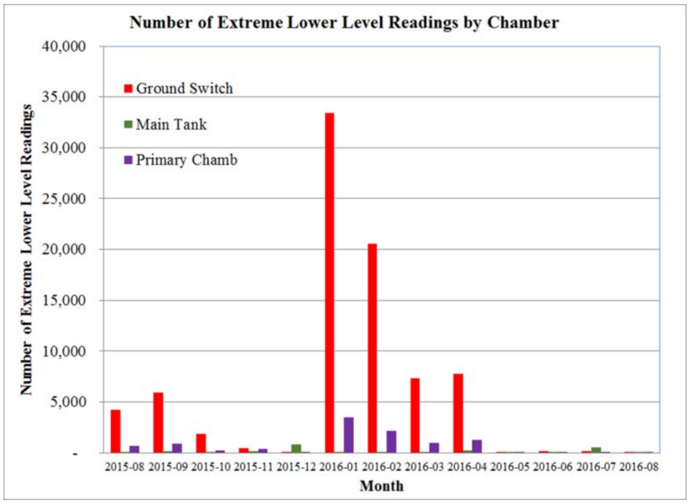


Figure 5-9 Number of Extreme Lower Level Readings by Chamber

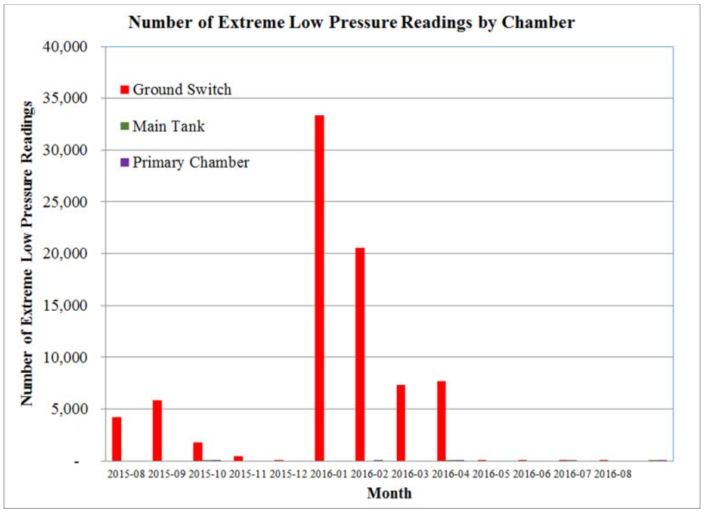


Figure 5-10 Number of Extreme Low Pressure Readings by Chamber

2. **Remote Reset:** The project compared false readings with timing of remote resetting activities.

   Result: As illustrated in Figure 5-11, the data suggests that some of the equipment had relatively high counts of bad data prior to reset, and that the number of bad data suddenly dropped to zero immediately following a reset. This indicates the likelihood of effectiveness of remote resetting to eliminate extreme low readings of the oil level and pressure sensor data. It further indicates that the source of the bad data may not be the physical sensor equipment because a sensor problem cannot be fixed by remote resetting of the equipment.

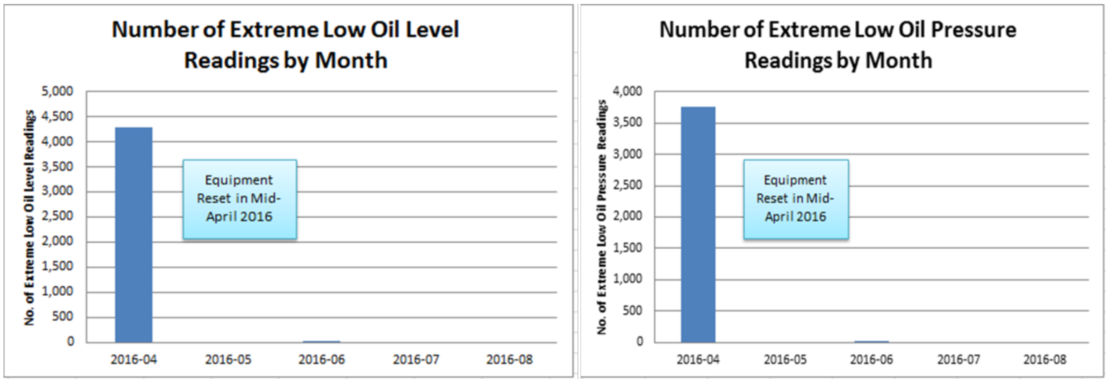


Figure 5-11 No. of Extreme Low Oil Sensor Readings by Month

3. **Weather Conditions:** The project compared monthly precipitation with total monthly false readings from oil sensors.

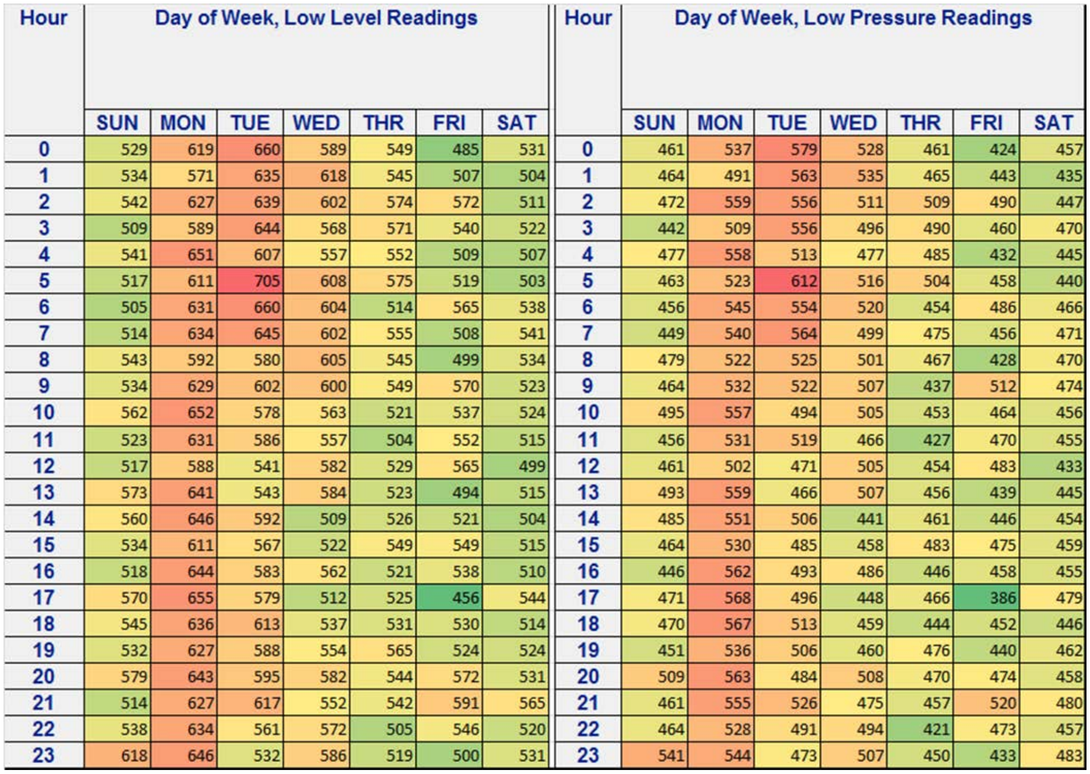
   Result: No statistical correlation could be found between the weather data and the number of the extreme low oil pressure and level data points. The correlation between the bad oil level data and precipitation is 0.5 with p-value = 0.1 and the correlation between bad pressure readings and precipitation is 0.4 with p-value = 0.2.

   A statistically significant correlation was found between false temperature sensor data and precipitation. The correlation between bad temperature readings and precipitation is 0.59 with p-value = 0.04. Correlation of data by day instead of the month did not reveal any difference in the results. However, the overall number of bad temperature readings compared to level and pressure readings is small (approximately 100 bad temperature data points versus over approximately 94,000 bad oil level and 82,000 bad pressure data points in 365 days).

4. **Day of the Week:** The project compared the number of false readings against the day of the week for patterns.

   Result: A trend was discovered between the number of recorded bad data points and days of the week. It was discovered that a high number of bad oil level and pressure data occurred on Mondays and Tuesdays. The trend tapered down during the rest of the week, through the weekends and picked up again late Sunday and early hours of the next Monday, consistently over the 365 days of the studied data.

   The number of bad data points shown in Table 5-4 over a one-week period shows a statistically significant decline from Monday to Sunday. The declining trend of number of bad oil level data points (extreme low level recordings) is statistically significant with a p-value = 0.006. The declining trend the number of bad pressure data points (extreme low pressure recordings) is statistically significant with a p-value = 0.012.



Hour	Day of Week, Low Level Readings							Hour	Day of Week, Low Pressure Readings						
	SUN	MON	TUE	WED	THR	FRI	SAT		SUN	MON	TUE	WED	THR	FRI	SAT
0	529	619	660	589	549	485	531	0	461	537	579	528	461	424	457
1	534	571	635	618	545	507	504	1	464	491	563	535	465	443	435
2	542	627	639	602	574	572	511	2	472	559	556	511	509	490	447
3	509	589	644	568	571	540	522	3	442	509	556	496	490	460	470
4	541	651	607	557	552	509	507	4	477	558	513	477	485	432	445
5	517	611	705	608	575	519	503	5	463	523	612	516	504	458	440
6	505	631	660	604	514	565	538	6	456	545	554	520	454	486	466
7	514	634	645	602	555	508	541	7	449	540	564	499	475	456	471
8	543	592	580	605	545	499	534	8	479	522	525	501	467	428	470
9	534	629	602	600	549	570	523	9	464	532	522	507	437	512	474
10	562	652	578	563	521	537	524	10	495	557	494	505	453	464	456
11	523	631	586	557	504	552	515	11	456	531	519	466	427	470	455
12	517	588	541	582	529	565	499	12	461	502	471	505	454	483	433
13	573	641	543	584	523	494	515	13	493	559	466	507	456	439	445
14	560	646	592	509	526	521	504	14	485	551	506	441	461	446	454
15	534	611	567	522	549	549	515	15	464	530	485	458	483	475	459
16	518	644	583	562	521	538	510	16	446	562	493	486	446	458	455
17	570	655	579	512	525	456	544	17	471	568	496	448	466	386	479
18	545	636	613	537	531	530	514	18	470	567	513	459	444	452	446
19	532	627	588	554	565	524	524	19	451	536	506	460	476	440	462
20	579	643	595	582	544	572	531	20	509	563	484	508	470	474	458
21	514	627	617	552	542	591	565	21	461	555	526	475	457	520	480
22	538	634	561	572	505	546	520	22	464	528	491	494	421	473	457
23	618	646	532	586	519	500	531	23	541	544	473	507	450	433	483

Table 5-4 Table of the number of bad data point per day of the week over the year of recorded bad data points with color coding that shows higher numbers in Mondays and Tuesdays

6.0 Learnings and Next Steps Summary

Overall, EPIC 1.09B/1.10B successfully evaluated and demonstrated appropriate maintenance over the life of the system, equipment resiliency and ways to extend the longevity and integrity of the system. There were several key learnings and next steps from the primary work streams within the project that could potentially support decision making and enable future improvements for this equipment.

- **Learning – Connector Type (Pinned Or Bare Wire) Impacts Resiliency:** Lifecycle testing of the connectors provided evidence that connections installed at the SCADA system are reliable and resilient. Exposure of electrical connectors to high temperature and humidity environments did not cause failure over three months of accelerated lifecycle testing. This length of accelerated life testing approximated 30 years of real world conditions. However, lifecycle testing did show a drop in connection strength after initial exposure to a high humidity environment. Bare wire connections were demonstrated to show a bigger drop in connection strength than pinned connections.

  Next Step – Explore Pin Wire Connections For Improved Resiliency: PG&E will explore leveraging pinned wire for the screw terminal type connectors in new underground vault installations for greater connection strength over time. This improvement in resiliency will potentially extend the life of condition monitoring equipment and support the robustness of the condition based maintenance system. While many connections are currently bare wire, next steps will focus on new installations as opposed to retrofit as a cost-effective approach.

- **Learning – Re-Torqueing Connections Positively Impacts Resiliency:** Re-torqueing the connectors one-time soon after the initial installation was demonstrated to be effective in maintaining good connectivity for the remaining duration of testing.

  Next Step – Explore Processes To Potentially Add a Re-Torque Of Connections After Installation: As a result of these learnings, PG&E will review current maintenance requirements post-installation, including potentially building in re-torqueing of the connections during the first few years of installation into maintenance plans.

- **Learning – Weight or Pull Has No Significant Impact on Connector Resiliency:** The application of weight to simulate inadvertent pull or mechanical stress on the connectors was also shown to have a minor impact on resistance, but did not significantly impact the performance of equipment. As a result of these findings, no next step will be explored at this time with regards to inadvertent weight or pull on connectors at installation or repair.

- **The Resiliency of Ambient Temperature Sensors Is Dependent Upon Location:** The project identified the failure of two ambient temperature sensors included in the demonstration during accelerated lifecycle testing. Both of these sensors were located outside of the RTU and data concentrator units, exposed directly to the elements of the test chamber.

  Next Step – Explore More Resilient Ambient Temperature Sensors for New Installations: While testing revealed the failure of two sensors, these devices can be monitored remotely, alerting the utility when replacement is needed. Temperature sensors with greater resistance to ambient temperature and humidity are available but they are more costly. With these considerations, there is minimal economic benefit to reducing failures through the replacement of previous sensors with more costly sensors with lower failure rates. However, due to these results, PG&E will explore more resilient components for new installations.

- **Learning – The SCADA RTUs Have Opportunities to Become More Robust:** The serial communication between the RTU box and the data concentrator was lost twice during testing. Testing indicated that it could be due to a resistive short as a result of moisture condensation and contamination at the connectors of the communication lines.

  Next Step – Enhance resiliency of the SCADA RTU: The communication link between the data concentrator and RTU is critical for receiving the data from the condition monitoring sensors. PG&E will be working with the manufacturer to improve the reliability of this component.

- **Learning – Location, Data Timing, Remote Resets and Precipitation All Impact Oil Sensor Data Integrity:** Statistical analysis of 365 days of actual historical data illustrated that oil pressure and level sensors for the ground switch chamber have significantly higher rates of false readings than other sensors. Further analysis illustrates that this may be attributable to sensor connection placement, as sensor connections made in the RTU expansion board were more likely to have a false reading. Additionally, a correlation was found to certain days of the week with significantly higher rates of false readings, which may be attributed to a change of vault temperature from weekend to weekdays. False oil temperature readings were found to be slightly correlated to precipitation. However, the overall number of bad temperature readings compared to level and pressure readings is small (approximately 100 bad temperature data points versus over approximately 94,000 bad oil level and 82,000 bad pressure data points in 365 days).

Next Step – Enhance Condition Monitoring Data Integrity: PG&E is working with the manufacturer of the RTU expansion board to improve the reliability. This includes further investigation of the false readings and correlation to days of the week. Currently, processes to discover and assess data issues are manual. As such, PG&E will also explore the development of automated data integrity tools for monitoring, alerting and quality checking the sensor data recorded by the PG&E SCADA system.

7.0 Data Access

Upon request, PG&E will provide access to data collected that is consistent with the CPUC's data access requirements for EPIC data and results.

8.0 Value proposition

Data obtained from monitoring the distribution network system is critical to understanding the heath of the network equipment. Failure of the condition monitoring system could limit PG&E's ability to proactively manage equipment before an issue occurs. This project demonstrated methods to ensure a resilient and robust condition monitoring system with new life cycle extension techniques and an evaluation of data integrity. Table 8-1 summarizes the specific primary and secondary EPIC Guiding Principles advanced by this technology demonstration project.

Table 8-1*: EPIC Primary and Secondary Guiding Principles*

Primary EPIC Guiding Principles			Secondary EPIC Guiding Principles					
Safety	**Reliability**	**Affordability**	**Societal Benefits**	**GHG Emissions Mitigation / Adaptation**	**Loading Order**	**Low-Emission Vehicles / Transportation**	**Economic Development**	**Efficient Use of Ratepayer Monies**
✓		✓						✓

The Network Conditioned-Based Maintenance technology demonstration project advances the following primary EPIC principles:

- *Affordability:* Extending the life of condition monitoring equipment may reduce the life cost of installation, maintenance, repair and replacement of this equipment. Additionally, being aware of potential problems with network equipment helps PG&E respond to required repairs before asset failures occur can potentially reduce the overall cost of operating the distribution network system by extending the life of major assets.
- *Safety:* Ambient temperature and oil sensors are designed to alarm upon conditions such as overheating of the equipment. Overheating could result in asset failure, potentially resulting in a safety risk. A well-functioning monitoring system reduces this safety risk.

This project also advances the following secondary EPIC principle:

- *Efficient Use of Ratepayer Monies*: Condition monitoring sensor failures and false readings from these sensors contribute to increased hours on troubleshooting and issue resolution. The project aimed to demonstrate the factors that are critical for equipment resiliency and data integrity of the monitoring system, allowing operations to optimally manage these sensors and data.

9.0 Technology Transfer Plan

To date, information about the results of this project has not been shared with others except for the manufacturers of the components. However, PG&E may potentially consider presentation and discussion at the following upcoming industry meetings:

- Institute of Electrical and Electronics Engineers (IEEE) 2017
- Edison Electric Institute (EEI) 2017
- DistribuTECH February 2018

10.0 Adaptability to Other Utilities / Industry

Many utilities have or are considering continuous condition monitoring of their distribution network systems. Understanding cost-effective life extension techniques such as enhancing connector resiliency, determining which types of equipment such as ambient temperature sensors are prone to failure under specific conditions, as well as a better understanding of data integrity are relevant considerations for utilities with condition monitoring equipment. Also, other industries that have underground non-electric infrastructure that are monitored, such as gas or oil, could benefit from the findings of this project.

11.0 Metrics

The following metrics as identified in CPUC Decision 13-11-025 were addressed in this project:

D.13-11-025, Attachment 4. List of Proposed Metrics and Potential Areas of Measurement	See Section
3. Economic benefits	
a. Maintain / Reduce operations and maintenance costs	5.2
b. Maintain / Reduce capital costs	5.1, 5.3
5. Safety, Power Quality, and Reliability (Equipment, Electricity System)	
d. Public safety improvement and hazard exposure reduction	5.1, 5.2, 5.3
e. Utility worker safety improvement and hazard exposure reduction	5.1, 5.2, 5.3

12.0 Conclusion

This project has captured key learnings that can be leveraged by other utilities and industry members to address the longevity of electrical connectors, sensors, and SCADA systems installed inside underground electrical vaults of distribution networks. Overall, the system is well designed and the components used are generally compatible with the environment where they are installed.

Although PG&E's system is robust, this project identified areas of improvement that PG&E will explore as potential next steps, including:

- Adding re-torqueing of connectors during the first few years post-installation to maintenance plans for improved equipment resiliency
- Leveraging more robust ambient temperature sensors and more reliable RTU expansion board for future installations
- Developing automated monitoring tools for improved understanding of data integrity

The SCADA and associated monitoring system can effectively be used to remotely gather real time data from within the electrical vaults. Bad data points can be monitored alerting the utility about on-going issues or failures that need to be addressed, including failed sensors. The system can be remotely reset to prevent bad data measurements from the oil level and oil pressure sensors connected to the expansion board of the data concentrator enclosure. Due to the results of this project, PG&E is working with the manufacturer on improving the reliability of the RTU and considering the development of a data integrity monitoring tool.

Sensors used within the underground vaults of the distribution system generally showed resistance to high temperature and humidity environments. Failures observed for ambient temperature sensors during lifecycle testing were isolated to sensors exposed to full ambient conditions of the simulation. Temperature sensors with greater resistance to ambient temperature and humidity are available but are more costly, reducing the benefit of replacing current sensors. As a result of these determinations, PG&E will consider a more resilient component targeted for new installations.

Lifecycle testing of the connectors provided evidence that connections installed at the SCADA system are generally reliable and resilient. Re-torqueing of the connectors can provide cost-effective support to the life expectancy of the system. PG&E will review of current maintenance requirements post-installation, including the potential to build in re-torqueing of the connections. PG&E will also consider leveraging pin wire connections as the screw terminal type connectors used in the equipment for underground vault installations for greater connection strength over time.

This project has confirmed the overall robustness of the monitoring and communication systems currently installed across the distribution network and demonstrated methods for improving the life and data integrity of its components. The results and learnings from EPIC 1.09B/1.10B will support a robust condition based maintenance program by enhancing equipment resiliency and data integrity.

13.0 Appendices: Exhibits A through G

Exhibit A.	**Sensor Technical Description**
Exhibit B.	**Environmental Testing**
Exhibit C.	**Testing Profile Details**