Applications of Aerospace-developed Corrosion Health Monitoring System (CHMS)

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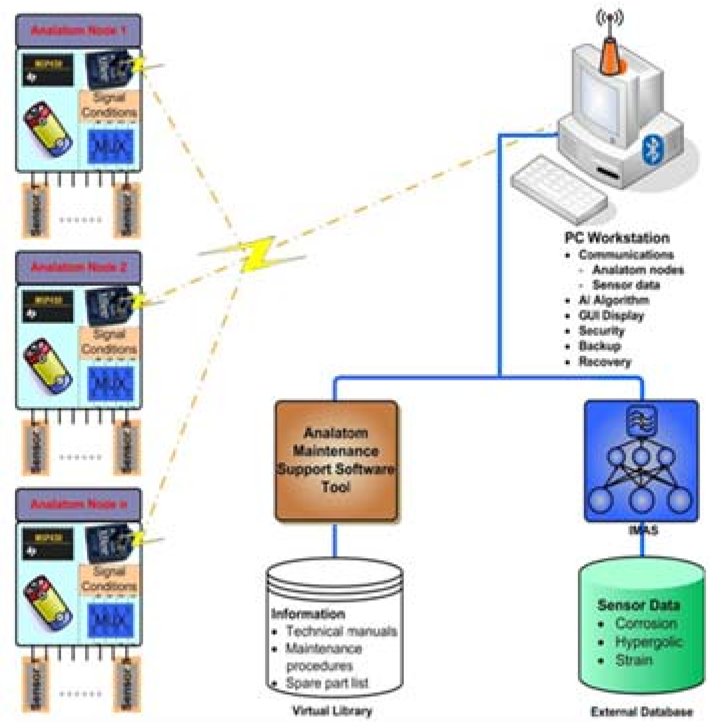
Technology

Embedded Structural Health Monitoring (SHM) and Prognostics (PHM) System

- Acquire, process, store, transmit corrosion rate (μLPR) and environmental data using open-ended sensor interface
- Wireless transmission to central server via ZigBee network addresses need for low-powered, small footprint solution
- Dynamic configurability allows additional sensors and adaptable data rates with minimal user technical support
- Process & display data in understandable, logical manner
- IMAS (Intelligent Management Analysis System) for analytics



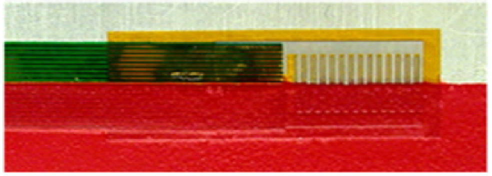
Benefits

- The Analatom micro Linear Polarization Resistance (µLPR) sensor based Corrosion Health Monitoring System (CHMS) is ideal to directly monitor mission critical components' corrosion rates/formation in inaccessible areas and under protective coatings
- The thin, postage stamp dimensioned LPR sensors when installed under the structure's coating allow continuous monitoring of structure corrosion rate and protective coating degradation
- For example, in 2010 total C-130 corrosion costs were $634 Million with $127 Million (or 20%) being spent on preventative maintenance
- By reducing unnecessary preventive maintenance and scheduling corrective maintenance actions based on condition, Air Force ROI study anticipates this system can reduce C-130 preventive maintenance alone by $12 Million (or 10%). One of <u>many</u> potential military platform applications
- CHMS technology has wide applicability: aircraft (fixed and rotary wing), bridges, buildings & facilities, equipment, pipelines & refineries, ships & submarines, stored munitions, large vehicles, and infrastructure, in general

Approach

- Analatom's µLPR CHMS, enhanced with its environmental sensing, continuously monitors—in situ—both corrosion rate & protective coating integrity/degradation
- When coupled with corrosion modeling, CHMS sensor data enables structure-wide prognostics for corrosion
- Linear Polarization Resistance (LPR) is an established electrochemical technique for fast, direct measurement of corrosion rates under conditions of electrolyte on metal
- This TRL 8 system is lightweight, internally powered, with postage stamp sized corrosion rate sensors allowing placement in difficult to access areas including behind panels, under coating systems, sealants, insulation, stealth coatings, etc.

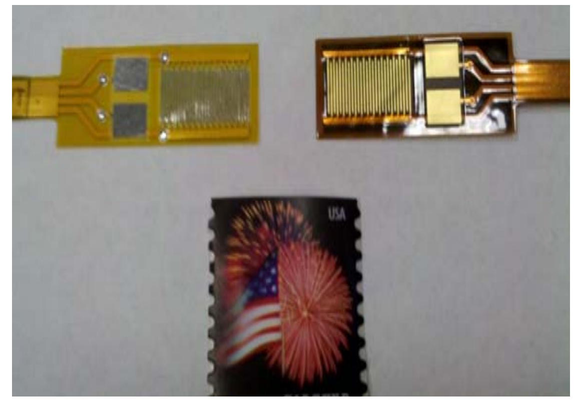
INSTALLATION ON C-130H



Analatom Corrosion Health Monitor

µLPR (Linear Polarization Resistance) Corrosion Sensor and
AN110-C Corrosion Health Monitoring System (CHMS) DAQ

- The thin (postage stamp-sized) flex-cable mounted micro LPR electrochemical sensor permits installation directly on structure or beneath any protective coating/sealant
- 2-Electrode µLPR configuration - Anode and Cathode are both active working electrodes
- 12-channel, internally powered, ruggedized field grade potentiostat data acquisition unit (MIL-STD) supports long-term remote and real-time SHM monitoring
- Capability: corrosion rate plus Time-of-Wetness, salinity, relative humidity, and temperature sensing for in situ monitoring of critical environmental factors needed in structural corrosion modeling



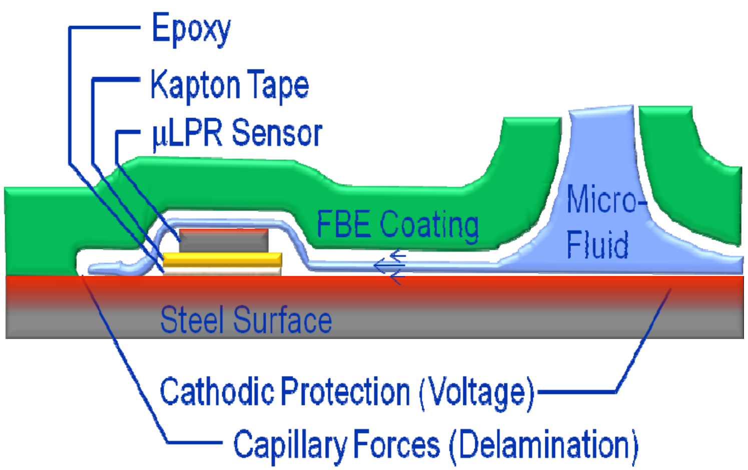
<u>μLPR Sensor Scope & Versatility</u>

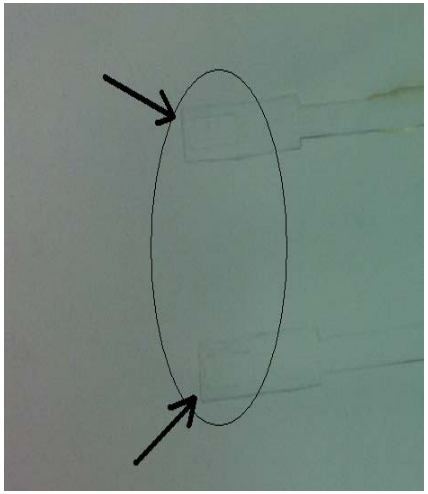
Sensor Material	**Configuration**	**Measurement**	**Comments**
Gold	Two Electrode	Time-of-Wetness (ToW)	LPR value used as threshold for ToW. Invariant to salt concentration
Nickel	Two Electrode	Salinity	Empirical relationship between salinity, LPR, and temperature
Carbon Steels, Aluminum Alloys,…	Two Electrode	Environmental corrosion; pitting	<u>Emulates</u> Structure's metal Coating integrity

Coating Integrity/Degradation

Corrosion Sensing beneath Coatings

- Over time, protective coating systems degrade and defect sites form permitting micro-fluid electrolyte transport of corrosive species along the metal-coating boundary
- Resulting coating disbondment increases diffusion rate, accelerating corrosion process over much larger area than defect size
- µLPR design allows installation beneath protective coatings, sealants, or insulation
- In situ monitoring of coating integrity gives early warning of coating degradation for preventive maintenance action in place of major repair
- Effective sensor radius, over time under coatings, can be 1-5 meters, depending on coating system's physical characteristics

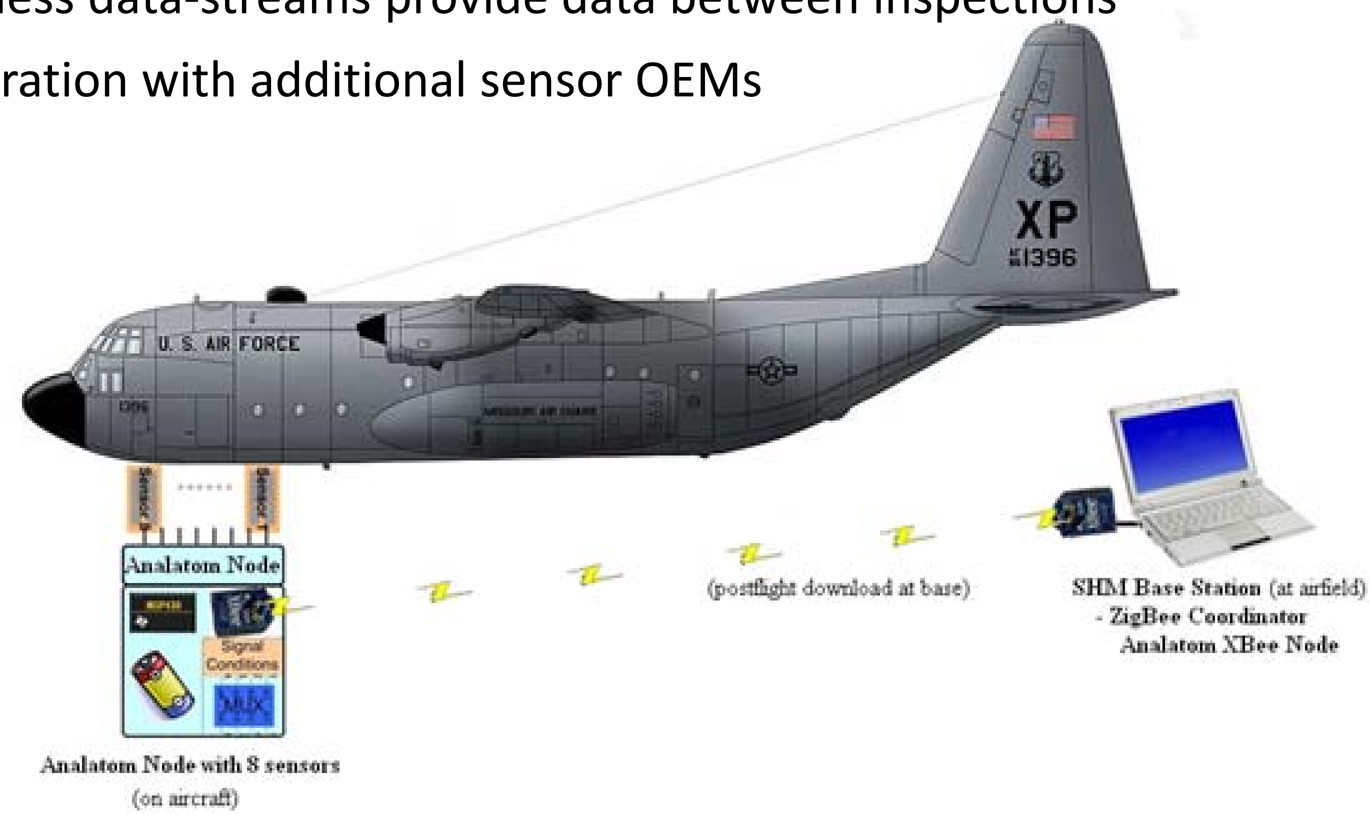




Applications – Aerospace

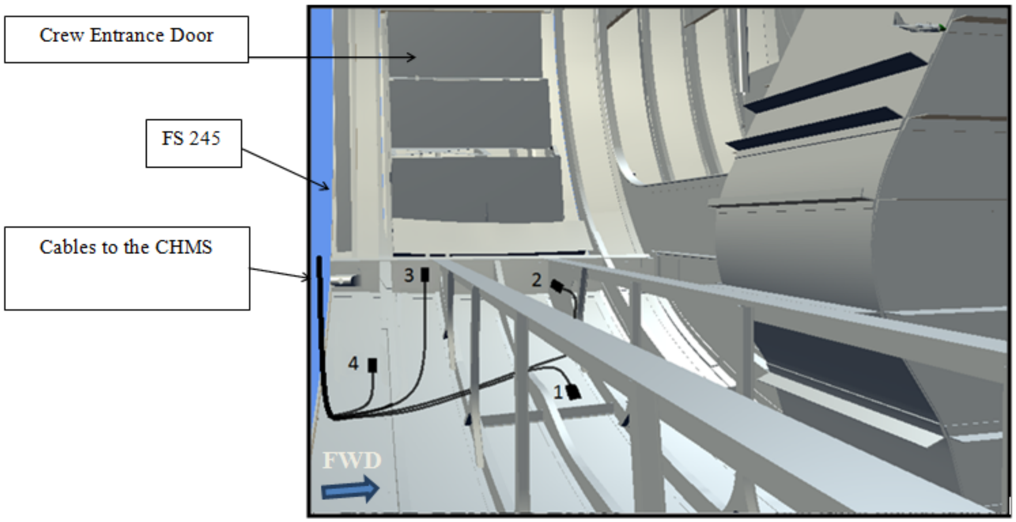
US Air Force C-130 Project (Overview)

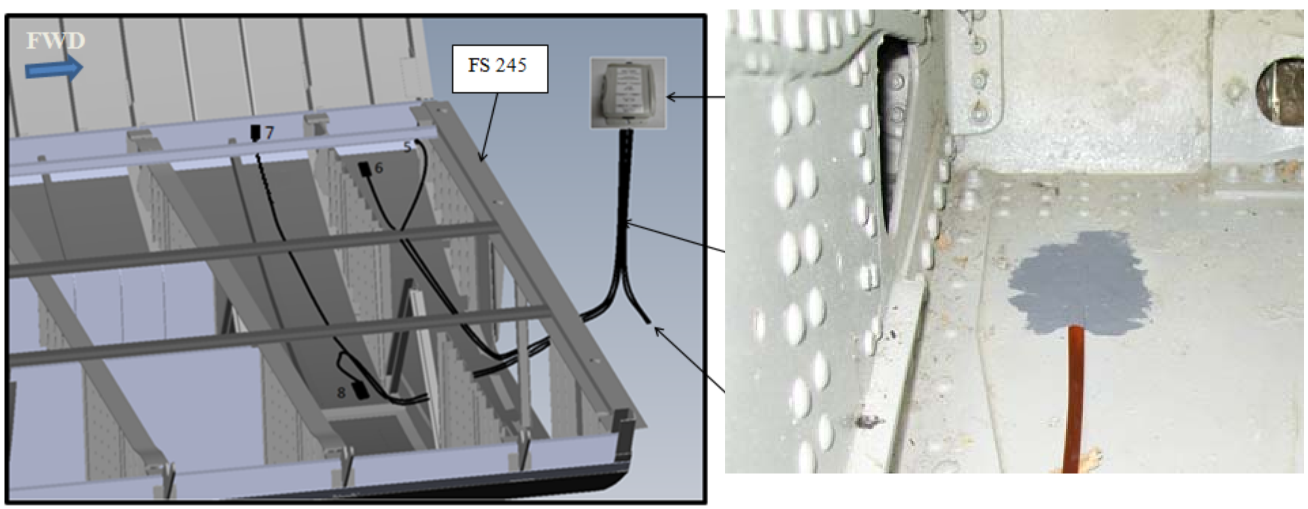
- Air Mobility Command Certified for C-130 Class II modification
- Eight sensors placed in areas of high corrosion
- Sensor measurements recorded remotely
- Wireless data-streams provide data between inspections
- Integration with additional sensor OEMs



Applications – Aerospace (cont'd)

Long-term C-130 Flight Test Installation





Results – Aerospace

Long-term C-130 Flight Test Results

- All CHMS criteria for successful operability, functionality, and survivability over the 17-month flight test were satisfied
- The wireless CHMS functioned properly over the flight test as technicians initiated and completed data download sessions
- The data record demonstrated contiguous, intact µLPR corrosion sensors, battery voltage, and temperature data logged
- The data record showed no spurious readings or false positives, which indicates rejection of EMI or electrical noise in a C-130 environment
- The internal battery voltage dropped only 0.02 volts in the 17-month field test attesting to the 7+ year operational life of the battery
- The CHMS survived all aircraft/environmental stresses applied
- Corrosion measurements were consistent with observed corrosion underneath the field-patch coatings upon removal
- Post flight test, an inspection and calibration test showed CHMS still operating within design specifications

Moving Forward – Aerospace

Air Force Base-wide C-130 Squadron Installation

- Patrick Air Force Base on Florida's east coastline chosen as installation site due to on-base corrosion problem
- Sale of ten 2nd generation AN110-M Corrosion Health Monitoring Systems (CHMS) for use on base's C-130 aircraft
- The in situ CHMS will hourly measure and record corrosion rates, relative humidity, external temperature, internal battery voltage, and internal temperature data
- In situ corrosion/environmental conditions monitoring of critical components, hard to access areas, and known hotspots enables maintenance personnel a condition-based decision making capability in support of CBM+ programs

Moving Forward – HH-60 Helicopter

Air Force Base HH-60 Pave Hawk Helicopter & Facilities Installation

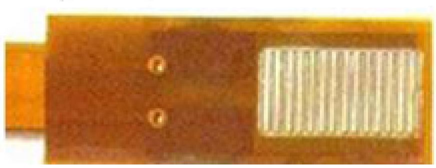
- Patrick Air Force Base on Florida's east coastline requested both rotary wing aircraft & support facilities installations due to corrosion problems
- Sale of fourteen 2nd generation AN110-M Corrosion Health Monitoring Systems (CHMS), to be installed on helicopters and at support facilities
- The in situ CHMS will hourly measure and record corrosion rates, time-of-wetness (ToW), salinity, relative humidity, external temperature, internal battery voltage, and internal temperature data
- In situ corrosion/environmental conditions monitoring of aircraft critical components, hard to access areas, and known hotspots, as well as real-time corrosivity levels around the base, allows maintenance and support personnel a condition-based decision making capability in support of CBM+ programs

Moving Forward – Coating Research

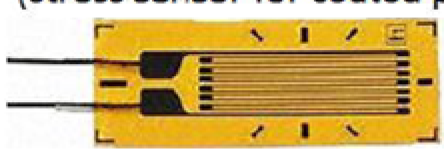
CHMS Enhancement to Support Monitoring Protective Coating Strain

- Corrosion growth under protective coatings causes coating disbondment from the metal substrate, resulting in coating blister development
- Based on research conducted at Bournemouth University, UK, initiation of blisters is measurable as increasing coating surface strain
- Adding a static structural strain sensing capability to the existing CHMS electronics' electrochemical/corrosion and environmental sensing enhances CHMS protective coating degradation monitoring
- The enhanced CHMS will measure and record corrosion rates, time-of-wetness (ToW), salinity, relative humidity, temperature, both structure and coating strain, battery voltage, and internal temperature data
- This in situ combined electrochemical, environmental, and structural sensor suite enables a Prognostics & Health Management (PHM) capability for CBM+ program maintenance and support personnel

μLPR Corrosion sensor

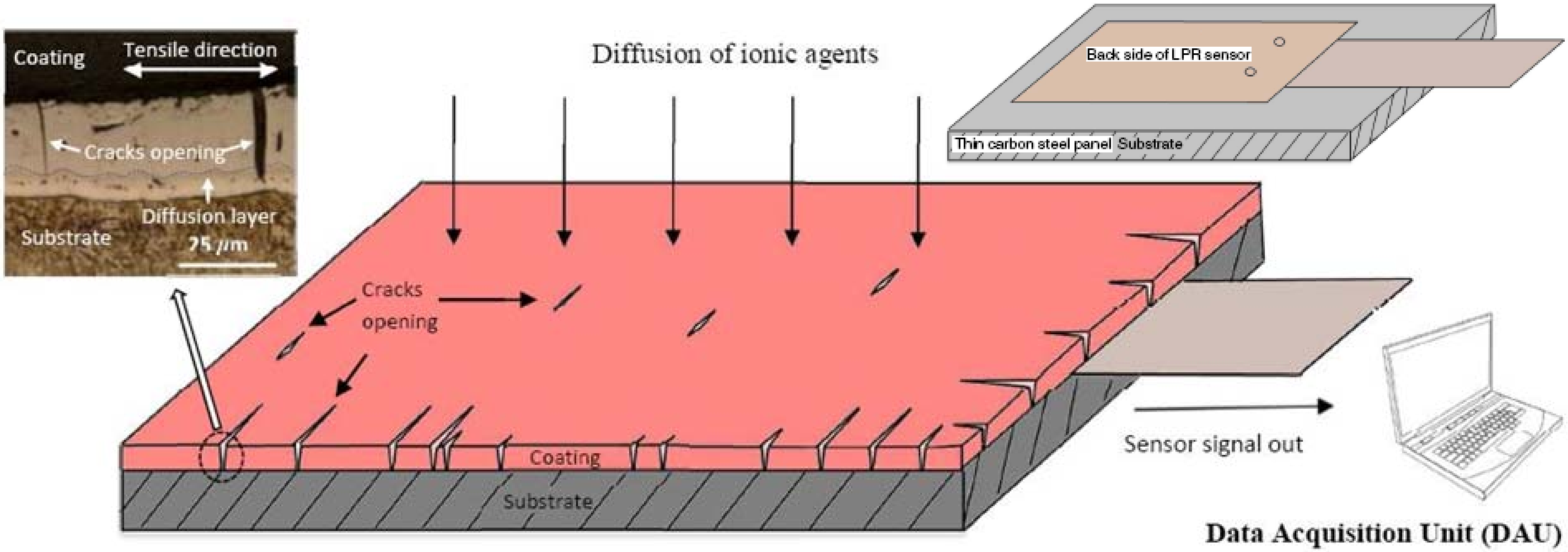


MEMS strain gage
(stress sensor for coated parts)



Applications – Protective Coating Research

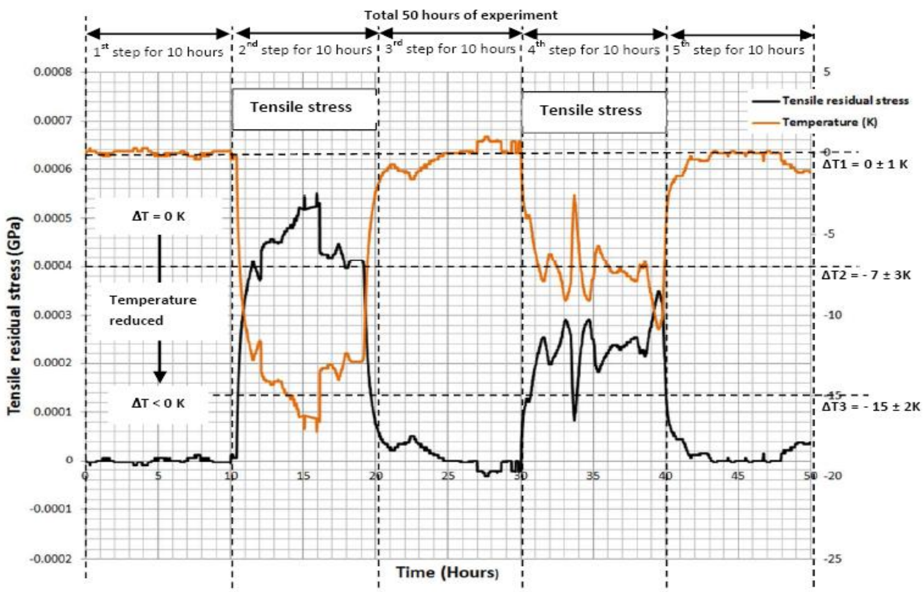
µLPR Sensing in Test Structures to Validate Coating Degradation Models



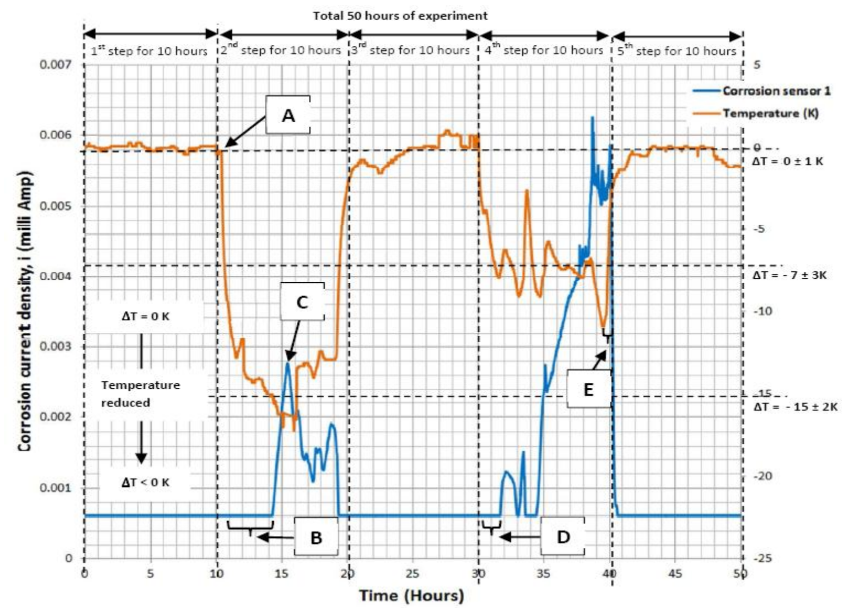
- Bournemouth accelerated corrosion testing of primer coated steel with purchased µLPR-based CHMS, while varying test structure temperature
- Coefficient of Thermal Expansion (CTE) of primer is greater than CTE of steel, accounting for tensile residual stress (calculable) in coating
- Tensile residual stress allows opening of protective coating's preexisting defects resulting in the evolvement of corrosion at the substrate interface
- Rate of corrosion progression is monitored by µLPR-based CHMS

Results – Protective Coating Research

Induced Stress and Follow-on Corrosion as Functions of Temperature



Tensile Residual Stress & Temperature



Corrosion Current Density & Temperature

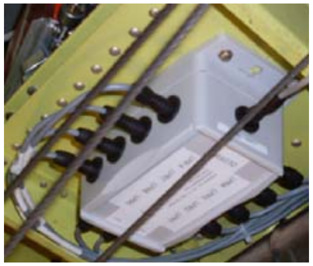
- Tensile residual stress in coating increases with reduction in temperature
- Increase in tensile residual stress opens and expands pre-existing structural defects in protective coating
- Corrosive agents can diffuse into interface causing corrosion rate increase

Corrosion Health Management Summary

- Corrosion occurs everywhere
- Embedded µLPR-based CHMS validated through laboratory testing, field tests, aerospace & industrial applications
- Improved structure/platform sustainment by in situ remote & real-time electrochemical/corrosion, environmental, and structural monitoring
- Demonstrated feasibility for implementable corrosion prognosis
- SHM data analytics can combine corrosion, environmental, and historical maintenance records for condition-based decision making
  - Large infrastructures require large prognostic windows of opportunity
  - Varied context requires complex correlation
  - Analysis infrastructures must scale to consider conditional contexts
- µLPR-based CHMS suitable for commercial & military applications: aerospace, bridges, buildings/facilities, pipelines/refineries, large vehicles, and infrastructure, in general

Examples of Actual CHMS Installations

Aircraft **Bridges** **Buildings** **Pipelines** **Universities** **Large Vehicles**



Sabreliner

Manhattan

Okinawa

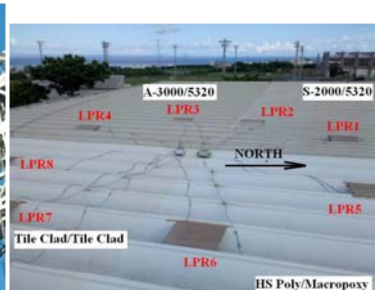
NYSEG, NY

Columbia

Hawaii

C-130

G. Washington



Torii Station, JP
(Warehouse Roof)

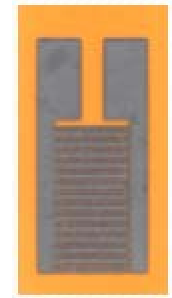
Buffalo, NY

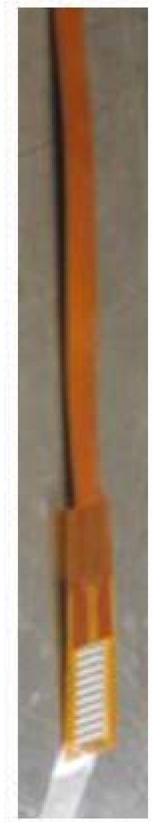
Bournemouth

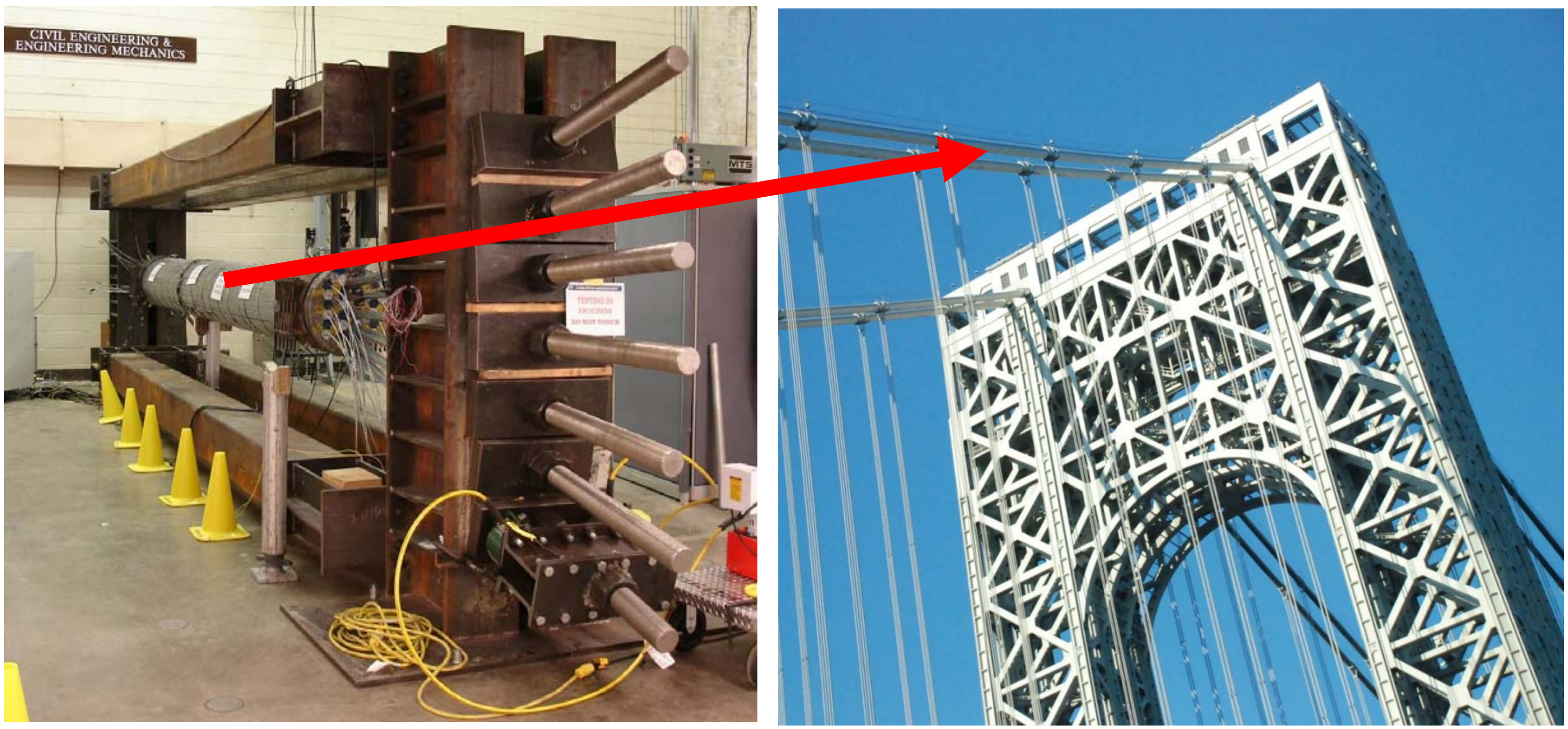
Tank
Museum, UK

Applications – Bridges

µLPR (Linear Polarization Resistance) Corrosion Rate Sensor and Monitoring Bridge Suspension Cables, from Lab to Field

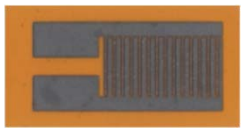




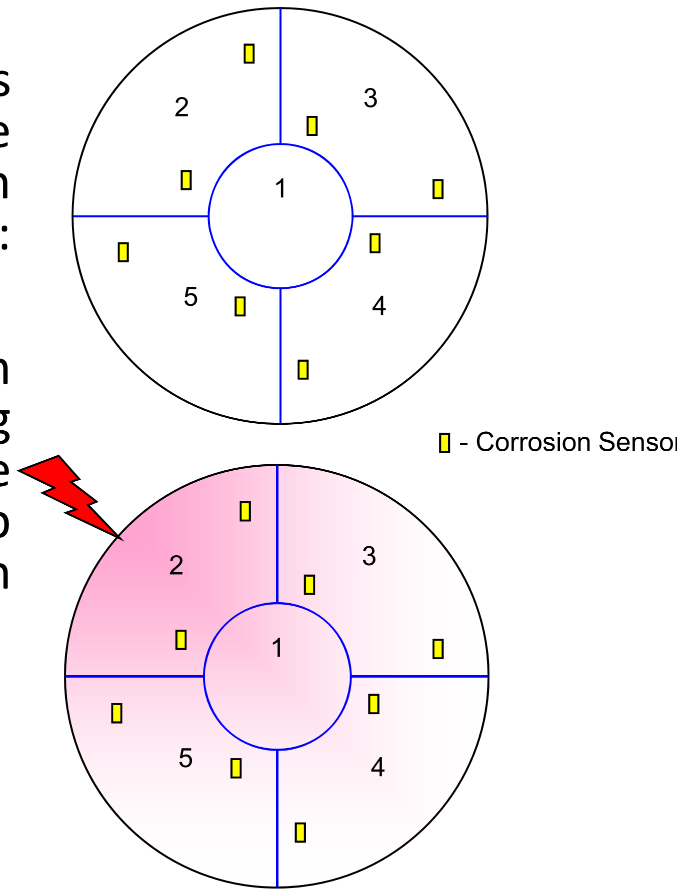


Applications – Bridges (cont'd)

μLPR Sensor System Bridge Suspension Cable Installations

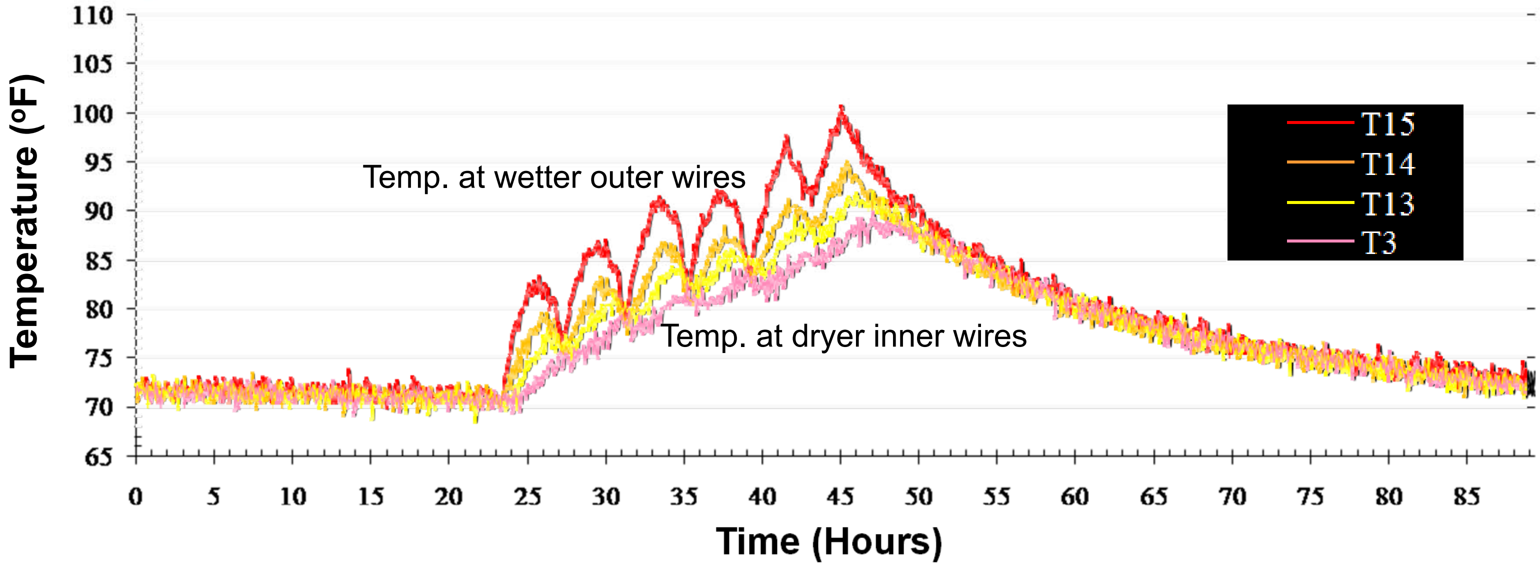


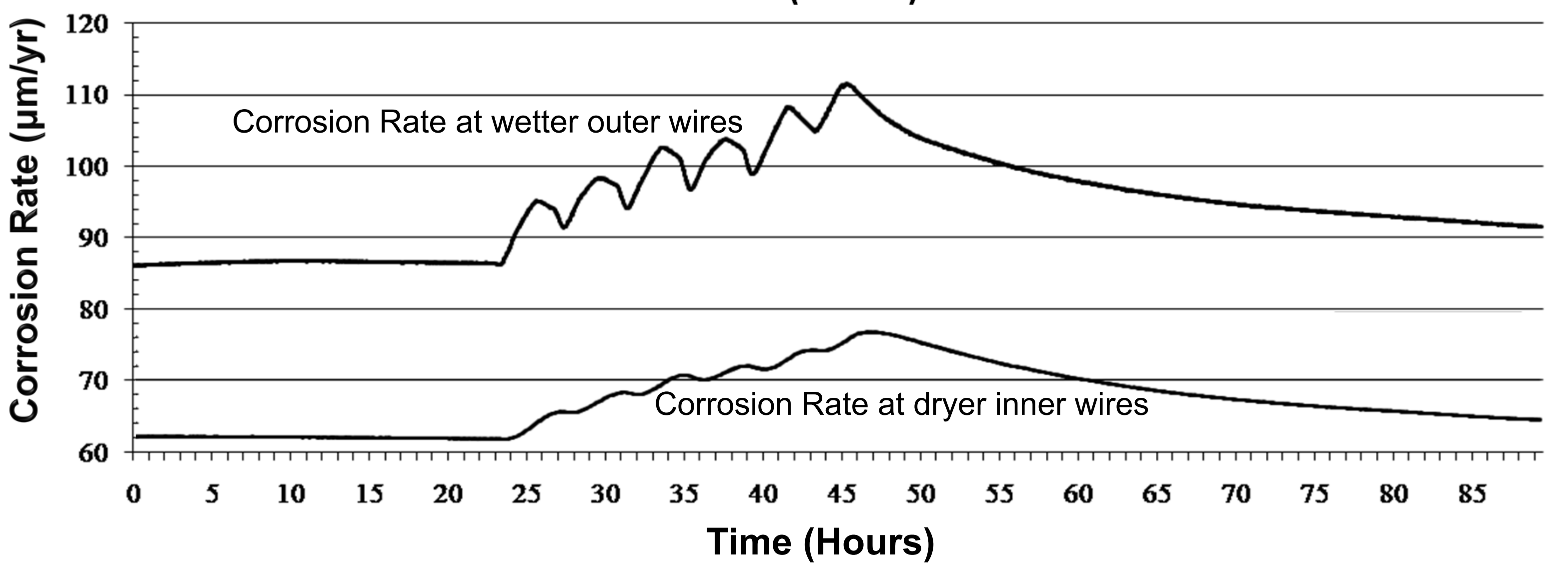
- The μLPR sensor location in any cable cross section will allow for corrosion rates in the cable to be displayed. Example given is with circular center section 1 and four quadrants: 2-5
- The thickness loss reading recorded at each sensor can be interpolated to the adjoining sensor. If, for example, a breach in the cable wrapping is present in quadrant 2, a map can be formed of cable's internal corrosion rate



Results – Bridges

Lab Testing: µLPR Corrosion Rate Correlates w/ Temperature & Moisture





Results – Bridges (cont'd)

CHMS Bridge Suspension Cable Monitoring Results in Field

Federal Highway Administration report (FHWA-HRT-14-023) detailing, in part, installation and performance of Analatom corrosion monitoring system on Manhattan Bridge states (p. 166):

> In conclusion, this study demonstrated that it is possible to measure corrosion activity inside main cables of suspension bridges. The information provided by such a system can be used to make more reliable estimations of the safety factor and remaining service life of such important structural elements as well as to help bridge engineers in conducting more efficient and cost effective inspections. Because of the continuous advancements in sensor and NDT technologies, it is important to pay attention to any new developments that can help improve such a monitoring system. (Emphasis added.)

Moving Forward – Bridges

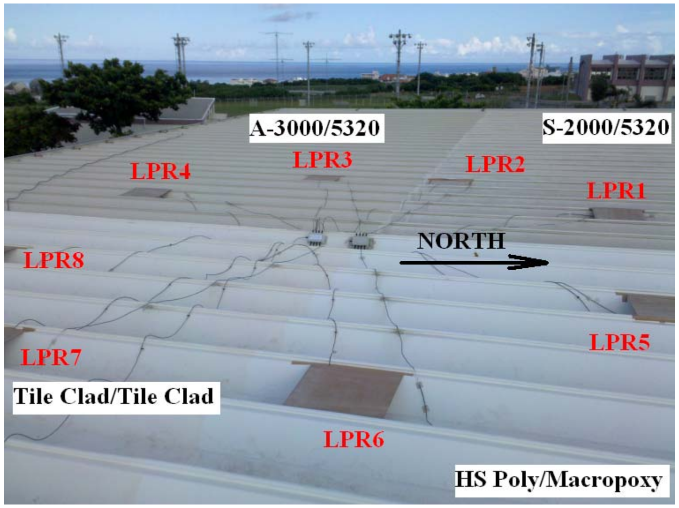
μLPR Sensor System Mandated by Ohio Department of Transportation

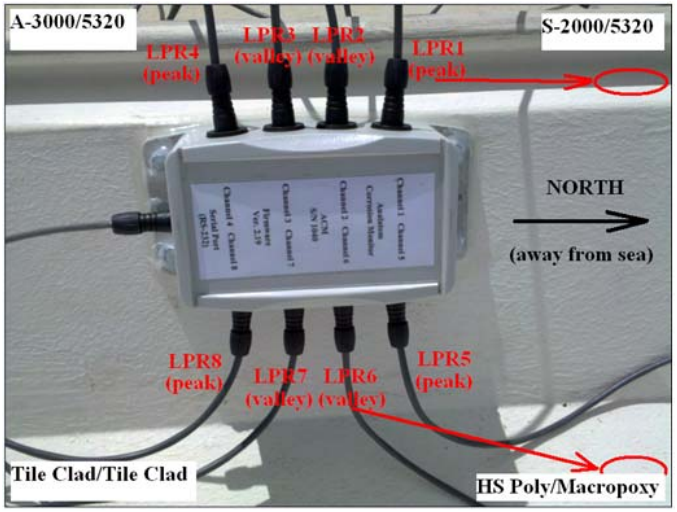
- Ohio DOT is planning to install a dehumidification system to reduce damaging humidity on the Anthony Wayne Bridge suspension cables
- The $8 million system pumps dry air inside fabric sheaths that surround bridge suspension cables, reducing inside dampness that promotes rust
- ODOT states the potential benefit was revealed during an inspection five years ago of the bridge's main cables, which date back to its original construction in the late 1920s
- As a contract requirement, ODOT specifically specified installation of multiple Analatom AN110-C CHMS in order to monitor dehumidification system performance over time

Applications – Buildings

CHMS Protective Coating Integrity Monitoring on Army base in Okinawa

- CHMS roof installations on critical building with corrosion issue due to location in subtropical region
- A 12-volt battery backed up satellite modem connected to the CHMS over a serial data cable periodically transmitted sensor data to Analatom headquarters in California
- Corrosion rate sensor pairs were attached to the metal roof and each pair painted over with one of four protective coating primer-paint combinations, one in each quarter
- Installing sensors under different coating systems allowed evaluation of each coating system's performance





Results – Buildings

CHMS Sensor Data Analysis Ranks Protective Coating Performance

- The integrated corrosion monitor-satellite modem system operated flawlessly in acquiring and transmitting sensor data, with battery backup sustaining the system during base power outages caused by seasonal tropical storms
- Visual inspection, after several typhoons, noted that the setup physically survived the high winds and rain of Category 3 typhoons
- During periods of wetness, the Analatom µLPR corrosion rate sensors under the primer and paint coatings were able to detect increased corrosion levels as a function of coating type, thus ranking the relative performance of each coating system
- CHMS withstood intense roof temperatures caused by direct solar radiation during clear days in summer
- In situ corrosion rate monitoring over time allows higher fidelity structural degradation information—especially in hard to access areas—and improved base maintenance decision-making capability

Moving Forward – Buildings

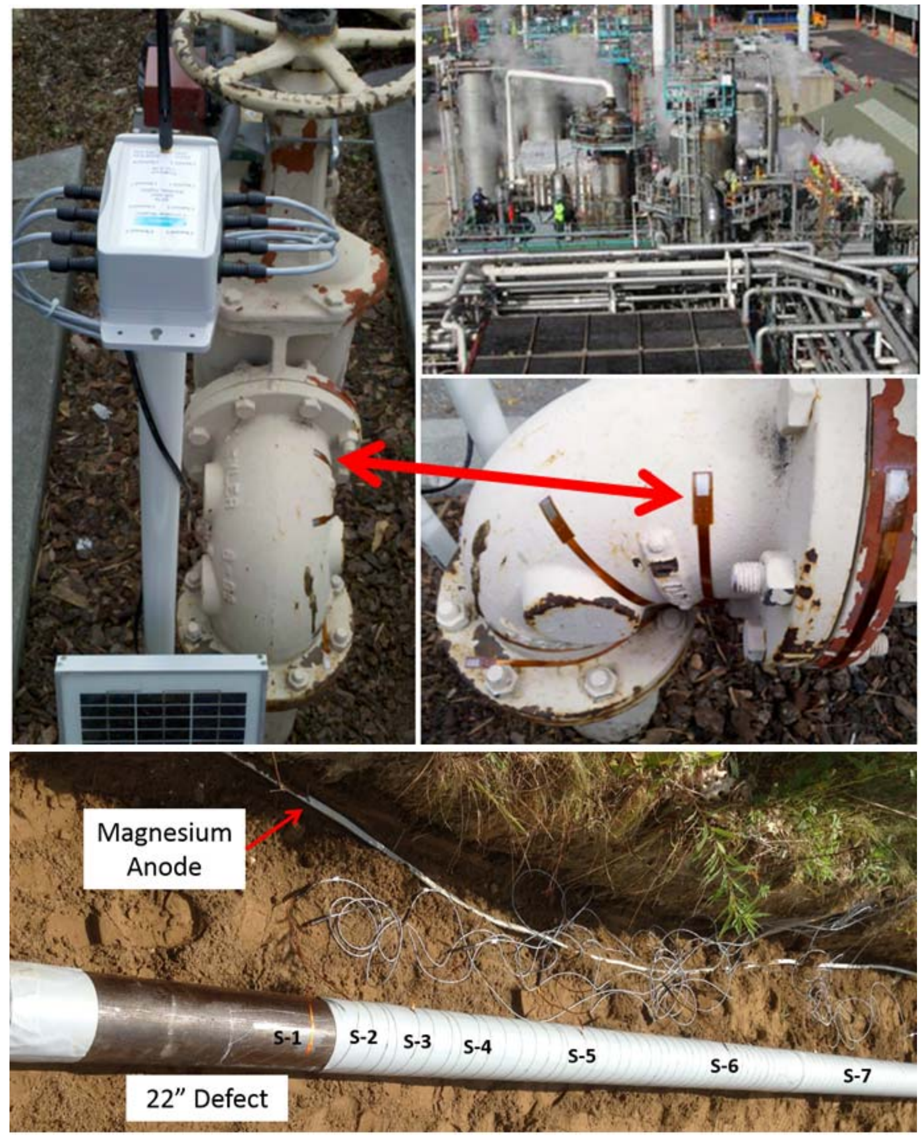
Environmental Condition μLPR Systems for Building Assessment

- Maek Consulting Pte Ltd, Singapore, adopted the specialized AN110-T for Architectural Engineering & Assets Management use
- For Architectural Engineering, using non-destructive techniques, they diagnose defects in buildings, e.g. detecting leaks and dampness, to propose materials and methods for remediation and repair
- For Assets Management, they assist clients in managing and developing building assets by evaluating the condition of buildings and structures to provide objective information for planning actions to preserve the property, including recommendations for prevention of both deterioration and defects
- Analatom has developed a strong working relationship with Maek engineering

Applications – Pipelines

Corrosion Monitoring for Pipeline Historical Problem Areas

- Pipe defects
- Loss of cathodic protection
- Valves
- Flanges, Couplings
- Welds
- Pumps
- Corrosion Under Insulation (CUI)



Applications – Pipelines (cont’d)

Corrosion Monitoring of Underground Pipelines

- Direct monitoring of buried pipeline external corrosion rates to compliment current corrosion control and management strategies
- Utilizes µLPR sensors in a linear array on a single flex cable allowing in situ quantification of the local corrosion environment under protective coatings
- Cellular link capability enables user to remotely monitor sensor data and, thus, pipeline and environmental conditions over 3G cellular networks
- Feasibility and return on investment is derived from ability to schedule maintenance on active pipelines before corrosion issues develop, that would require major repair and potential replacement
- Designed as a compliment to current corrosion inspection strategies and a potential solution where inline inspection is currently not possible

Results – Pipelines

Line Pipe Monitoring Project's Phase III Major Results

- The CHMS external 6-volt solar panel and internal rechargeable battery are of adequate capacity for the application year round
- The EMI shielded multi corrosion rate sensor Hybrid Flex cable design (40') simplified field installation, while reducing spurious noise injection and retaining sensor accuracy
- Cellular module based wireless communication design proved reliable
- No operational issues, errant behavior, or false positive corrosion indications, despite high-voltage power lines directly overhead
- The sensor-on-coupon experiment validated the Analatom µLPR corrosion rate sensor accuracy in determining structure mass loss
- The 6-month field Beta tests in New York demonstrated the CHMS design, fabrication, and testing process produced systems that are functional, robust, and reliable in natural gas pipeline corrosion monitoring applications

Moving Forward – Pipelines

Commercializing the Phase III CHMS Design

- The Phase III CHMS will be transitioned to a commercial corrosion and environmental condition monitoring product for the natural gas pipeline industry
- The commercial version will transmit sensor data over a cellular link to a customer's secure cloud provider account
- The data can be directly downloaded and analyzed by customer engineering and maintenance personnel
- The CHMS will use an HTTP protocol that is compatible with the cloud-based data service's API (Application Programming Interface), the set of protocol definitions needed to communicate with the service
- The CHMS will support a 4G LTE Cat M1 cellular module, since cellular carrier support for 3G will be diminishing in the coming years
- The lower power 4G LTE Cat M1 cellular module is designed specifically for battery powered embedded systems

Applications – Large Vehicles

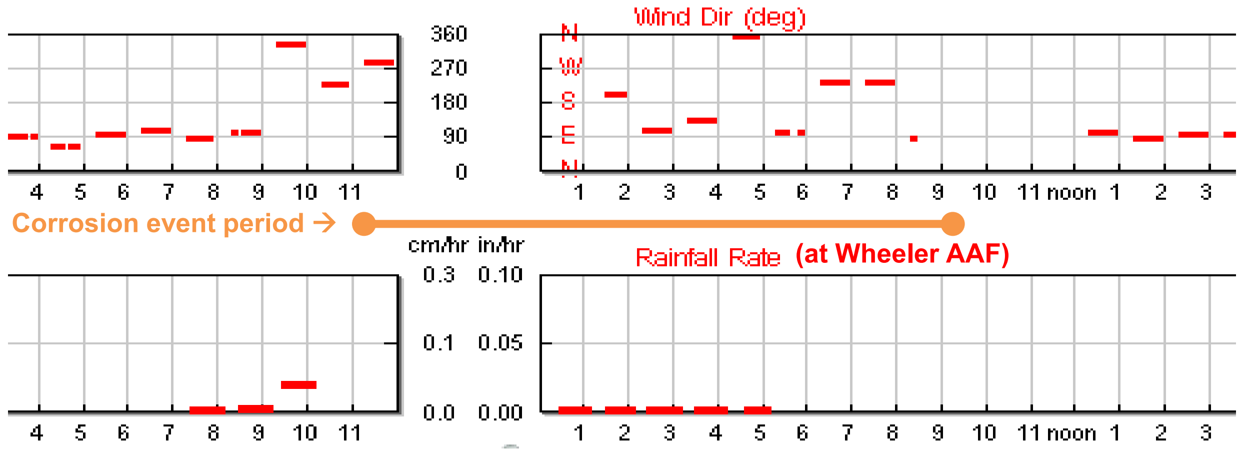
CHMS Monitoring Fleet of Trucks Ravaged by Corrosion

- CHMS systems fitted
- Data collected:
  - Corrosion rate (µLPR sensor)
  - Satellite imagery (Internet)
  - Weather station data (Internet)

Results – Large Vehicles

Diagnostic Results of Corrosion & Environmental Conditions Monitoring

Local Weather Station Data (from Internet)



- Rainfall, this night, concentrated into period around 10 p.m.
- Wind straight from north, wetting exposed vehicle area around Sensor #1
- Corrosion onset detected ~1 hour after start of rain (1 hr. sampling period)
- Time of wetness extended by low temp. (64-67° F) at dew point until 8 a.m.
- Data allowed decisions for orientation of corrosion sensitive vehicle areas away from historical local rain directions during prolonged storage/parking

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