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UPDATE ON APPLICATIONS OF CORROSION COULOMETERS

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ABSTRACT

A review⁽¹⁾ and current status description is provided for the corrosion coulometer. The device was developed for monitoring corrosion on unpainted weathering steel structures and to provide an assessment of steel corrosivity in the local environment. The technology has been field tested in eight states and diverse environments. Developments of the coulometer have focused on providing inexpensive and convenient implementation, as well as, tailoring the sensor to address specific needs. Design modifications have been made to the sensor to address specific application needs and an inexpensive data logging device has been developed to provide for ease of use and acquisition of detailed corrosion data.

Keywords: atmospheric corrosion, corrosion rate, weathering steel, field test, corrosion sensor, coulometer, steel structures

INTRODUCTION

Elevated rates of corrosive deterioration of steel structures are caused by exposure to aggressive environmental conditions. Some very aggressive conditions are due to the confluence of natural and man-made conditions. For example, poor drainage and debris accumulation promote locally high corrosion rates. Resultant strength loss and crack susceptibility are due to cross-section thinning and to formation of notches leading to concentration of stresses¹. Figures 1-4 provide examples of corrosion problems observed on large painted steel structures in aggressive environments where dirt and debris

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accumulated. These types of problems are generally avoidable by attention to design details; providing for water runoff, keeping debris to a minimum, and developing knowledge of the structure's local corrosion environment. Design details are based partly upon an average set of corrosive conditions. Typically, data collected from a limited variety of sites (rural, industrial and marine) with boldly exposed (rapid drying surfaces) are used to define the general environment². Sensor readings are capable of providing information on the local corrosive environment including effects of on-going maintenance procedures (deicing, cleaning and drainage control). The corrosion coulometer, developed by White and Leidheiser^{3,4}, has been placed and corrosion data collected on structures in Maine, Michigan, Pennsylvania, New Jersey, North Carolina, New York and Hawaii, representing varied environments^{5,6}. Corrosive environment data collected at a preconstruction site in Maine aided in the material selection and structure design. Comparisons of these field sites were made to established corrosion tests sites at Kure Beach, North Carolina, and at South Mountain, Bethlehem, Pennsylvania. Maintenance decisions can be improved through the use of real-time and archived data. Results show that improved design and better maintenance methodologies, as well as cost savings, are useful outcomes of the coulometer technology.

Corrosion's effect on structural durability and on longevity of bridges is an important issue. Two illustrations of corrosion's damaging and costly impact are the temporary closing of the Williamsburg Bridge in New York City, and the deicing salt attack of weathering steel bridges in Michigan. The capability for monitoring atmospheric corrosion on steel structures and improving maintenance programs is now available.

Electrochemical sensors, designed for wet corrosion environments, have been in use for 3-4 decades. Corrosion occurring in the presence of a continuous, bulk, electrolyte phase (Figure 5) can be monitored using conventional electrode configurations. The critical difference between wet and atmospheric corrosion is the lack of bulk (continuous), ion-conducting liquid electrolyte (Figure 6). Measurements of atmospheric corrosion with electrochemical sensors, are not easily accomplished due to characteristics of the electrolyte film on the corroding surface. However, thin-film electrolyte characteristics were used in the design of the atmospheric corrosion monitoring device termed the corrosion coulometer.

Significant Issues

In this paper, three issues are addressed, including, (1) monitoring or assessing corrosion using boldly exposed specimens for comparison to typical service conditions involving dirt and debris; (2) predicting corrosion on site including actual service conditions; and (3) development of cost-effective data acquisition technology. While these issues relate most directly to weathering steel structures, there is a link to corrosion-related problems involving steel-reinforced concrete, painted steel structures (see Figures 1-4), and other corrosion related structure degradation problems.

MONITORING CORROSION

A common method⁷ for evaluating the atmospheric corrosion resistance of materials is to expose specimens at specific test sites such as Kure Beach, North Carolina, shown in Figure 7. Note that many plate specimens occupying several square feet must be exposed for long time periods to obtain rate information using destructive evaluations. The method suggests exposing the flat, plate specimens at 30° inclination, facing south without shade, and keeping them sufficiently elevated to avoid ground moisture. These conditions are clearly different from exposures encountered at bridge sites; horizontal and vertical surfaces, random orientation to sunlight, complete shading of some components, presence of run-off water, or proximity to a body of water.

Figure 8 shows atmospheric corrosion test results obtained by Horton⁸ for low-carbon, copper-bearing and weathering steels in an industrial environment. The information is useful for materials comparison and development. However, additional studies must be performed to evaluate potential design problems encountered in applications. For weathering steel, the potential problems were identified and recommended practice was established, particularly with respect to bolt spacing and patterns and drainage considerations⁹. The recommended practice is based upon a limited variety of exposure sites representing a range of environmental conditions. Therefore, additional consideration must be given to the specific construction site and the use of innovative or exotic designs. Further, caution must be exercised to assure that the service conditions do not violate the environmental conditions established for the structure during the design, fabrication and erection stages, (for example, accumulation of dirt or debris forming poultrice corrosion conditions or ineffective drainage mechanisms).

PREDICTING CORROSION

The monitoring methods mentioned previously can easily be described as unwieldy when information is required for a specific structure's site. Information of the specific site's corrosivity is important for design, maintenance and rehabilitation. For example, no simple relationship exists between rural, industrial or marine exposure site data versus prediction (or

explanation) of the corrosivity at the overpass levels of the 8 Mile & Lodge (M-10) intersection in Detroit, Michigan (Figure 9). The second and third overpass levels exhibited aggressive and benign corrosion, respectively. Atmospheric corrosion data as a function of height is a rarity. Also, existing data obtained at one site does not address problems associated with a specific structure such as drainage or dry-off problems. With current technology, it is possible to evaluate proposed construction sites and structures as they were constructed or while they are in service to enable realistic corrosion assessments for design, maintenance, or rehabilitation.

The corrosion coulometer (Figure 10), invented by White and Leidheiser¹⁰, consists of a copper cup with a layer of glass beads on the bottom and a steel screen resting on the beads. When saturated with water, galvanic action between the cup and screen produces a current in an external connection. As the cell dries out, current decreases to zero when the cell is completely dry. Total output ($i \times t = \text{coulombs}$) of the cell is stored in a microcoulometer, e.g. an E-Cell (Series 560, Basic Laboratory Design, Inc., Los Angeles, CA 90045, or alternative: Model 120-PC, Curtis Instruments, Inc., Mt. Kisco, NY 10549), which can be read at any time. The coulometer collects airborne contaminants, debris, and water from precipitation, traffic spray, or leaky bridge joints. As the steel screen corrodes, corrosion products similar to that on a structure form on the steel, glass beads and underlying filter paper.

The coulometer's compactness and electrically generated information are the two advantages over traditional plate penetration methods. The coulometer can be used for extended periods, with readings at any desired time interval, another major advantage over plate measurements. Conversely, plate penetration curves require removal of a plate to determine its mass loss, requiring many plates to establish a penetration curve. A single coulometer can establish a penetration curve. Cumulative coulometer readings mimic plate penetration curves because the coulometer screen is constructed of the same material as the plate. The screen weathers to form a protective oxide layer in a similar manner as the plate material. Remote reading of corrosion coulometer values reduces the need for regular visits to the test site.

The steel screen feature of the corrosion coulometer was specifically designed for measuring general, uniform corrosion, i.e., corrosion on existing bridges, for evaluation of proposed weathering steel bridge sites; and for evaluating chemical plant corrosive vapor environments or aeronautic launch facilities having corrosive-exhaust emissions. The steel material selected for the screen component can be A36, A588 or other types with specific test purposes. Ongoing maintenance procedures directly influence the coulometer readings (bridge deicing, cleaning and drainage control) enabling immediate feedback.

The coulometer was not designed to monitor crevice or localized corrosion or for directly characterizing painted steel structures. However, information derived from the current coulometer designs would be useful in estimating crevice and localized corrosion and assessing painted steel degradation rates.

Original testing of the corrosion coulometer was reported by White and Leidheiser³. Laboratory evaluation by monitoring successive wet/dry cycles and exposure on the roof of a building at Lehigh University for 20 weeks showed excellent correlations with corrosion of adjacent steel panels (Figure 11, where Model 1 was a similar design and prototype for Model 2). The next coulometer testing was at six locations on existing steel structures⁶. Figure 12 shows some results of the study on A588 steel at the following sites: an I-beam outside the ATLSS Laboratory at Lehigh University in Bethlehem, Pennsylvania; at selected locations on Pennsylvania Dept. of Transportation bridges in Bethlehem (BETH) and Montourville (MVILLE); on a New Jersey Turnpike Commission bridge near Newark (NJTP); and on two Michigan Dept. of Transportation bridges in Detroit (8MILE and I-96). Steel panels for weight-loss studies were installed on bridge locations only and results yielded a corrosive ranking for sites: 8MILE > I-96 > NJTP > BETH > MVILLE. The ranking is in agreement with Figure 12 results. The correlation of cumulative coulometer readings with mass losses of adjacent panels showed the corrosion coulometer generates useful data in agreement with bridge inspection observations.

ADDITIONAL STUDIES

Corrosion coulometer and plate penetration test sites were established for short-term studies at Hawaii, North Carolina and Maine. The objective of the Hawaii and North Carolina studies was to compare weathering steel corrosion rates, verifying suitability of weathering steel for specific applications in the Hawaiian environment. The objective of the Maine preconstruction site study was to better characterize the environment to facilitate selection of materials for construction of a new bridge across the Androscoggin River, between Brunswick and Topsham, Maine. At each site, A36 and A588 steels in the form of penetration plates and corrosion coulometers were exposed to atmospheric conditions for periods of up to 12 months.

Hawaii and North Carolina

Corrosion coulometer results for Hawaii and North Carolina sites are shown in Figure 13. Lower readings for the Hawaii site show lower corrosivity of the steels versus the North Carolina site. An interpretation of the results is that the Hawaii site [approximately 1.6 km (1 mi) inland] has lower chloride deposition rates, better drying conditions and more frequent rainfall washoff of corrosive deposits than the North Carolina site (0.25 km inland). The A588 steel exhibits lower average readings than A36 steel. These findings are consistent with plate penetration results shown in Figure 14. The A588 steel results shown in Figure 14 agree with results obtained by Townsend and Zoecola².

The comparison of Hawaii coulomb and penetration data for both A36 and A588 materials shows reasonable agreement of time dependencies (Figures 13 and 14). A similar agreement exists between the North Carolina data for the A36 material. However, for North Carolina data obtained with A588 material, coulomb values are not as low as would be predicted for consistency with the penetration data. One explanation is the formation of a protective film on A588 material which has a lower reactivity than the other samples. Townsend, et al¹¹ suggested that the transition from initial oxide to protective oxide occurs more rapidly in aggressive environments. Protective oxide can increase coulomb efficiency of the coulometer. This effect suggests that additional useful information may be extracted from corrosion coulometer studies.

Maine

Results from a six month study at the Androscoggin River site in Maine yielded low rates of corrosion based upon plate penetrations and coulometer readings. Plate penetrations were approximately 6 μm . Coulometer readings were up to 2 C. Both data sets were near the lowest detection limits for plate and coulometer measurements. Results were consistent with low overall rates and lower rates for A588 versus A36 material. Additional details of the experiments and results are given by Wilson and Granata¹².

MONITORING SECTION LOSS

Figure 15 shows coulometer data obtained on an I-beam exposed outside the ATLSS Laboratory on Mountaintop Campus at Lehigh University. The I-beam diagram in Figure 15 identifies locations of 6 coulometers attached to the beam around its cross-section and southern face. In the upper portion of Figure 15, the open diamond symbols indicate times at which the beam was sprayed with salt solution when snowfall occurred. Coulometer readings showed sharp increases following salt applications. In the summer, the beam was washed by hosing with fresh water to assure removal of residual salt and debris. Coulometer readings showed lower rates during the summer following salt removal. Lower coulometer readings on southern-facing lower flange and web locations versus top and northern-facing locations were attributed to more rapid drying of the surfaces. The coulometer provided detailed information on corrosivity versus events (salting/deicing maintenance) and specific locations representing differing microenvironments related to construction details.

Figure 16 shows a diagram of section loss locations in an aggressive environment (see Figure 3). Losses were more severe on the left side of the cross-section. Comparison of corrosion coulometer results in Figure 15, ranking corrosivity versus placement on beam to location of losses (Figure 16), suggests a good correspondence. The decision to discontinue maintenance and painting of the hangers seen in Figures 3 and 4 as well as the residual cross-section shown in Figure 16 resulted in significant corrosion loss in an aggressive marine atmosphere as was discussed in Fisher et al¹. The ATLSS corrosion coulometer measurements shown in Figure 15 would suggest that relative losses of the cross-section shown in Figure 16 are correlated. However, the right and top surfaces in each case indicate lower relative section losses. In addition to load bearing reduction due to section loss, corrosion leads to notching, stress concentrations and possibility of cracking.

CURRENT STATUS AND IN-PROGRESS DEVELOPMENTS

Two types of developments are underway: 1) an electronics package (corrosion monitor) for data acquisition, storage and transmission, and 2) modification of sensor design for accurate response and alternative services. These are briefly described.

Corrosion Monitor Features

The corrosion monitor (Figure 17) has two modes of operation which are described as manual and automatic. These descriptions refer to the method of uploading data from the monitor into a computer.

In the manual mode of operation it is necessary to make a physical connection between the monitor and computer using a null-modem cable. Commands from the computer will then cause the monitor to transmit the data to the computer where it may be saved. Data transmission does not erase the data stored in the monitor. A separate command must be issued to erase data (possible in manual mode only). At each transmission the complete data file is transmitted. Typically, the manual mode is used as a stand-alone corrosion monitoring device when a hardwire or cellular connection is not desired or practical. Data may be acquired for up to 18 months depending upon battery life [approx. 1 year/set (6) of AA batteries]. The data will be retained in non-volatile memory for up to ten years if the data acquisition battery is expended.

The automatic mode of operation is intended for remote data collection. In this mode the monitor would be connected to a modem and telephone line (or cellular phone) at a remote site and would transmit its data to a central computer at pre-programmed times.

For remote operation the corrosion monitor is able to be programmed with; a telephone number to dial, the day of the week and the time to make the call, and the interval between calls. The call interval is set as a number of days; thus the monitor will send its data at the same time every day or number of days. When the corrosion monitor is preparing to transmit its data, first a relay is energized within the monitor. A contact on this relay, wired to one of the external connectors, allows power to be switched on to the modem (and cellular phone, if used). After this has happened and a dial tone is sensed, the corrosion monitor will dial the pre-programmed telephone number. When the receiving computer responds, initial handshaking procedures are carried out by the modems at each end and communication established. The monitor then transmits its data file, which includes starting and ending times and dates together with a checksum character to permit basic error checking by the receiving computer. When transmission is complete the monitor will switch off the modem by deenergizing its relay and resume normal operation until the next transmission. In the event that no connection is made when the number is dialed, the corrosion monitor will try again for a total of three times. After that it will shut down and not try again until its next programmed transmission time.

The corrosion monitor, in its basic form, is designed to be an off-the-shelf corrosion assessment system. A unit can be prepared for use by installing a fresh battery, connecting the sensor, starting the electronics, transporting to the monitoring site and mounting the unit on the desired site. The unit can be serviced on-site or returned for service (data readout) at intervals of up to 18 months. Alternatively, the unit can be connected to a hardwired or cellular modem and hourly data reviewed daily or every several days or weeks.

Sensor Design Modifications

The initial design of the corrosion coulometer was based upon a requirement to assess corrosion associated with poulitice or debris on horizontal or accumulative steel surfaces. This requirement was met and an additional need based upon this work was identified for condensing surfaces. A design modification permitted successful corrosion monitoring of condensing surfaces. Other designs were developed for sensor inclusion in a main suspension cable of the Williamsburg Bridge and in concrete. These alternative designs are expected to be evaluated in future studies.

CONCLUSIONS

Several conclusions may be drawn, namely:

- The corrosion coulometer provided useful information for weathering steel structure corrosion environments for bridges, existing structures, and proposed sites. The coulometer is as effective as plate penetration tests to assess site corrosivity and can provide more detailed information, conveniently, particularly in short time intervals (1-24 months).
- Predictive assessments of corrosivity can be performed as periodic or real-time measurements to permit remediation before severe damage occurs.
- These studies demonstrate research capabilities for determining site-specific data and corrosive mechanisms.
- Specific studies can be effectively implemented using the corrosion coulometer, such as evaluation of cleaning strategies and procedures for corrosion abatement.
- A convenient and cost-effective means has been developed which permits acquisition and use of corrosion data for in-service monitoring and maintenance planning concerning steel structures.

ACKNOWLEDGMENT

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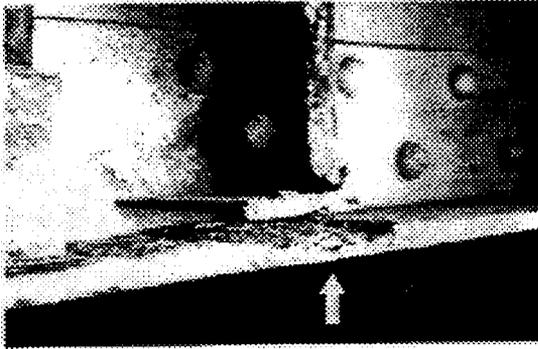


Figure 1. Corrosion notched flange angle below diaphragm where dirt and debris accumulated.

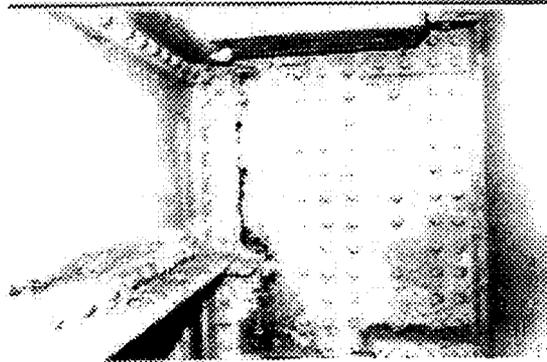


Figure 2. Corroded web penetration along vertical angle legs of stringer and connection to floor beams.

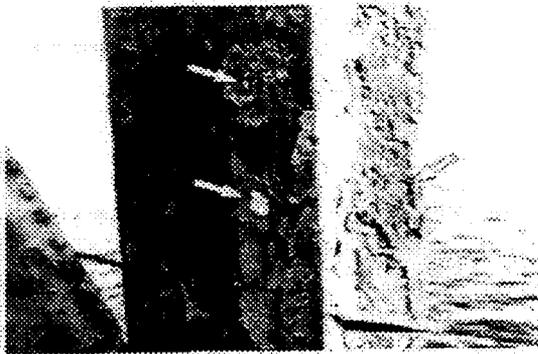


Figure 3. Corrosion penetration of riveted hanger components on the Grand Narrows Bridge, Nova Scotia.

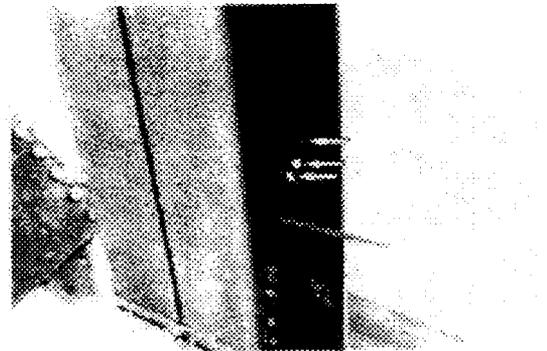


Figure 4. Corrosion penetration of riveted hanger from Grand Narrows Bridge, Nova Scotia.

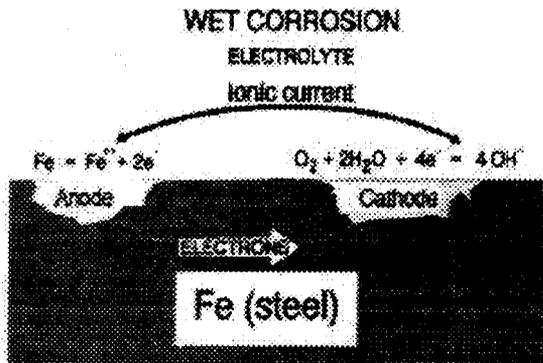


Figure 5. Schematic of wet corrosion with bulk electrolyte.

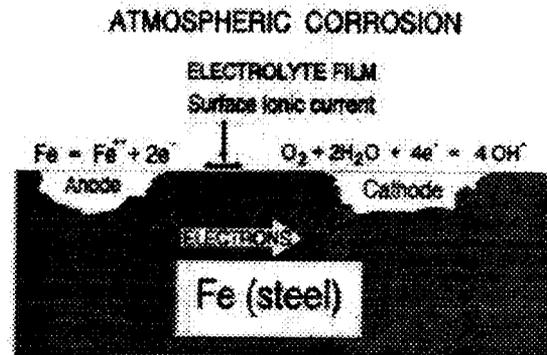


Figure 6. Schematic of atmospheric corrosion with film electrolyte.

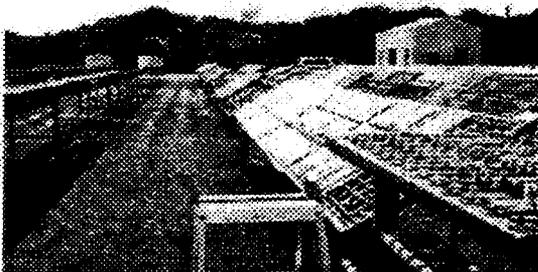


Figure 7. Corrosion test exposure site at Kure Beach, North Carolina.

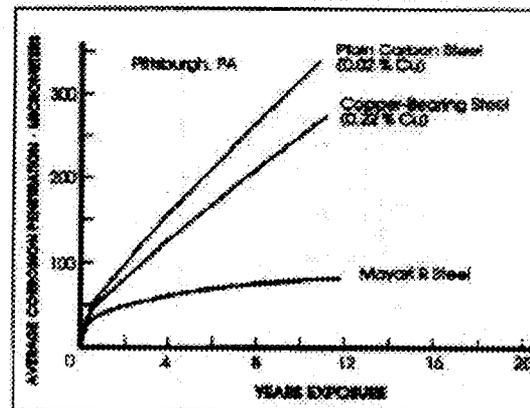


Figure 8. Corrosion of steels in industrial atmosphere.

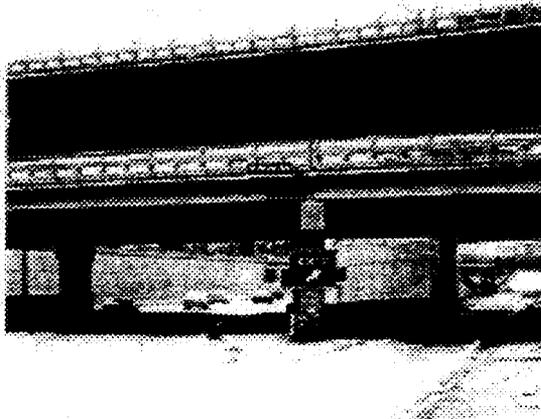


Figure 9. Bridges at 8 Mile Road and Lodge Expressway (M-10) in Detroit, MI.

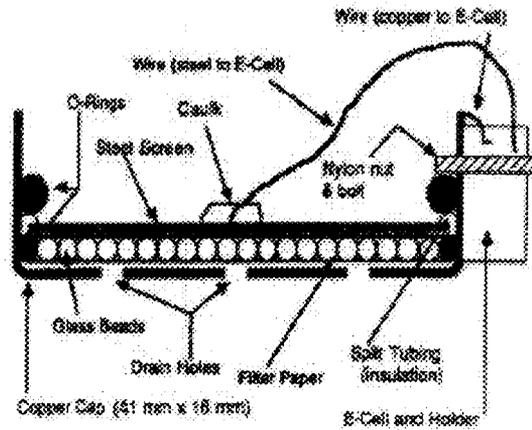


Figure 10. Model 2 coulometer, cross-section.

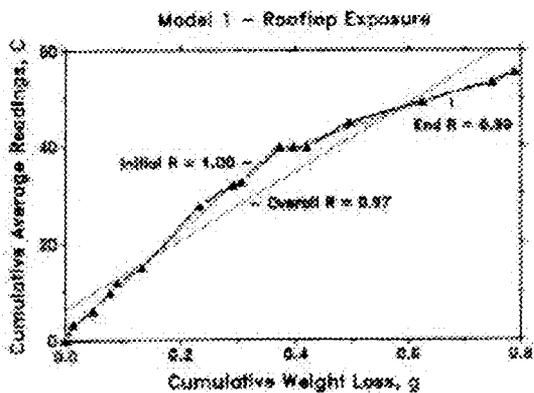


Figure 11. Model 1 results with correlation coefficients, R, for overall data set, initial set (to 0.4 g) and end set (remaining data).

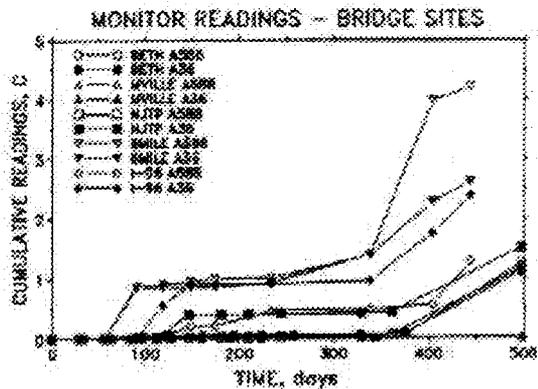


Figure 12. Coulometer results at bridge sites.

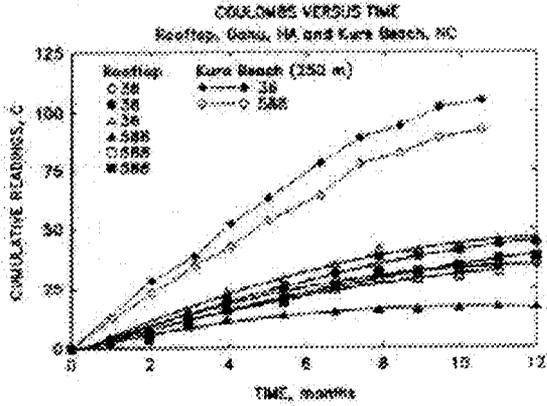


Figure 13. Coulombmeter results for HA and NC.

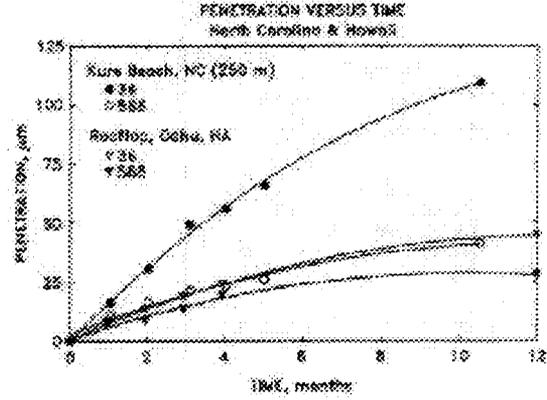


Figure 14. Plate penetration results for HA and NC.

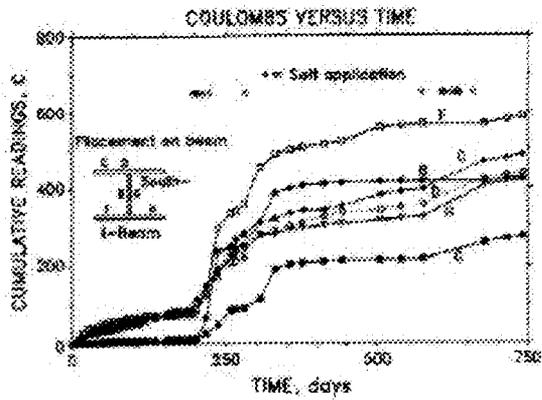


Figure 15. Monitor readings at top, web and flange on I-beam exposed at Mountainop Campus location.

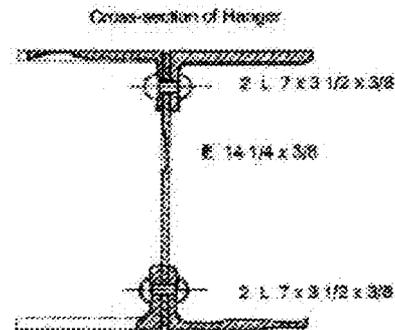


Figure 16. Hanger, Grand Narrows, Nova Scotia.

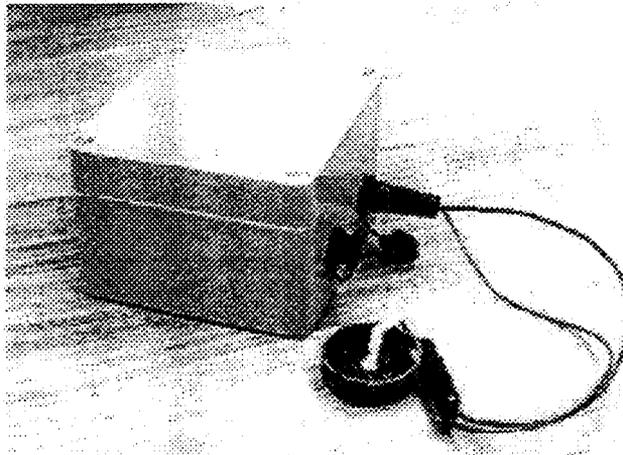


Figure 17a. Corrosion coulometer (cup diameter, 41 mm) and monitor unit. Production units may be less than half size shown.

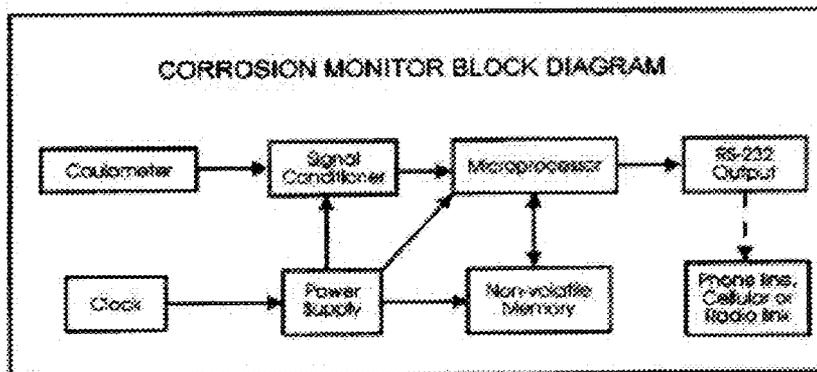


Figure 17b. Block diagram of monitor unit electronics.

Electronic corrosion coulometer characteristics:

- Records corrosion as it occurs (time-referenced)
- Zero resistance ammeter input circuit
- Battery operated (1 year/set of AA batteries)
- Sealed, waterproof case
- Memory capacity for 18 months
- LED to indicate proper operation
- Memory power for 10 years
- Microprocessor controlled.
- RS-232 port downloads recorded data into computer or handheld communications device