Corrosion Control of Municipal Infrastructure Using Cathodic Protection

Robert A. Gummow, P.Eng.
CORRENG Consulting Service Inc., 369 Rimrock Road, Downsview, ON, M3J 3G2, CANADA
(a wholly owned subsidiary of Corrosion Service Company Limited)

Presented at the NACE International Northern Area Eastern Conference
Ottawa, ON, October 24-27, 1999

Published in “Materials Performance”, Vol. 39 (2), February 2000

Since its introduction in 1824, cathodic protection (CP) technology has developed to become a fundamental tool for preventing corrosion on municipal infrastructure. Potable water storage tanks and piping, prestressed concrete cylinder pipe, reinforced concrete structures, bridges, parking structures, underground fuel tanks, and effluent treatment clarifiers now benefit from this technology.

The first use of cathodic protection, generally attributed to Sir Humphry Davy[1] in 1824 (although it may have been Michael Faraday who did most of the development)[2] involved the application of zinc to protect the copper sheathed hulls of sailing ships in the Royal Navy. Despite this early inaugural application, cathodic protection did not become a recognized corrosion control technology until over 100 years later. R.J. Kuhn,[3] as a result of experience gained from controlling electrolytic corrosion on iron water mains in New Orleans, promoted the use of cathodic protection for steel gas piping. This technology was rapidly adopted by the oil and gas pipeline industry to protect steel piping where its effectiveness was typically demonstrated by the flattening of a cumulative leak curve as illustrated in Figure 1, and by satisfying the -850mV$_{cse}$ criterion that was proposed by Kuhn.

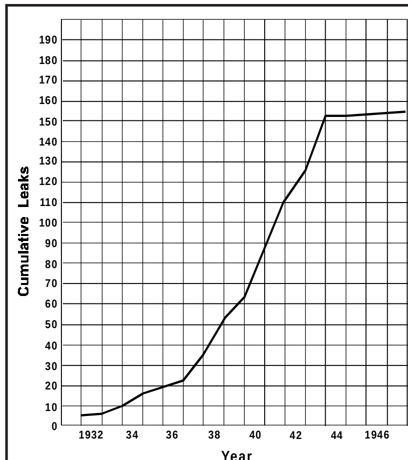

FIGURE 1 • Cumulative corrosion leaks on the steel mains in the business section of Houston. Mains installed in 1927-30. CP completed first part of 1944.

(redrawn from: Wahlquist, Hugo W., Fanett, Henry M., Practical Use of Galvanic Anodes, CP Symposium, NACE, 1949, p140)

Development of cathodic protection technology proceeded primarily in the oil and gas industry rather than the municipal sector, because it became erroneously accepted that the cause of breaks on municipal water piping was due to the brittle nature of grey cast iron rather than corrosion. Fitzgerald[4] in 1968 however, was able to prove that, in Detroit, the fundamental cause of water main breaks was corrosion. Hence, even though considerable corrosion control efforts were focussed in the early part of this century on iron water mains, cathodic protection technology was not adopted by the municipal water works industry until many years later. Presently, cathodic protection is routinely applied to many structures considered part of a municipal infrastructure.

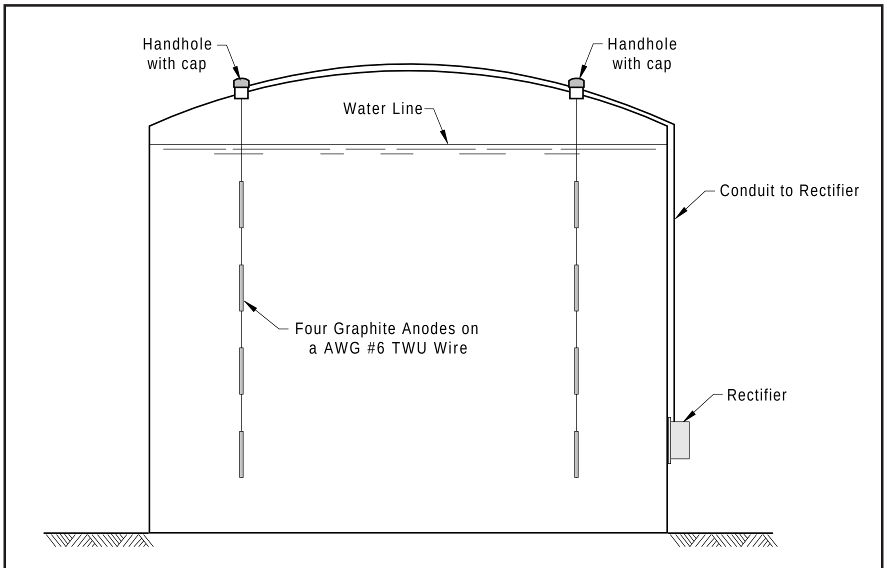

FIGURE 2 • Cathodic Protection of the Interior of a Water Storage Tank using Graphite Anodes Suspended from the Tank Roof

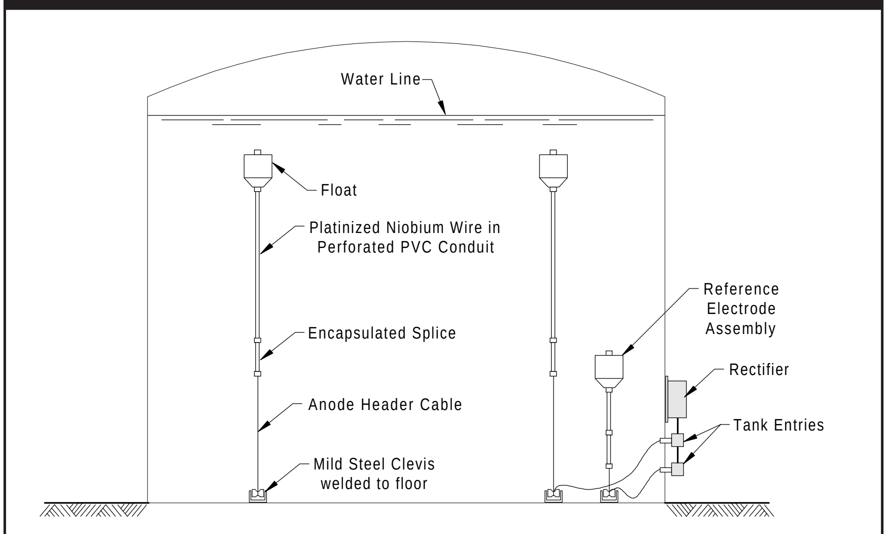

FIGURE 3 • Cathodic Protection of the Interior of a Water Storage Tank using Platinum Clad Niobium Anodes Suspended from Floats

POTABLE WATER STORAGE TANKS

The first widespread use of cathodic protection in municipalities was for the corrosion control of the internal immersed surfaces of steel potable water storage tanks beginning in the 1950's. The first systems were impressed current, because of the high current requirements due to the tank surface being bare or poorly coated, and typically consisted of graphite anodes suspended from the roof as illustrated in Figure 2.

Damage from ice during the winter led to various developments to combat this problem including: anodes suspended on springs encased in a stretchable rubber sheath; suspended aluminum cable[5] anodes that would be consumed before freeze-up with new ones installed each spring; and, with the advent of lighter platinum clad materials, suspension of the wire anode array on floats, as illustrated in Figure 3.

During the last 20 years the use of coatings, such as vinyl, high build epoxy, and 100% solid urethane, on the internal surfaces has significantly reduced the current requirements such that galvanic magnesium anode systems have become technically viable and economically attractive. Not only does cathodic protection control corrosion at coating defects, but it is claimed[6] that it also extends the service life of the coating, provided that the tank-to-water potential produced by the cathodic protection system is not excessive. In well coated tanks, positioning of the anodes to achieve uniform current distribution is less critical than in bare or poorly coated tanks, so that it is easier to design a cathodic protection system that is both durable and effective for a service life of 20-30 years.

There are currently two NACE recommended practices[7,8] and an AWWA[9] standard addressing the application of cathodic protection to potable water storage tanks.

POTABLE WATER PIPING

Iron Mains

During the 1970's, in many Canadian cities the appearance of corrosion leaks on ductile iron piping, that had been installed for less than 10 years in some instances, alarmed the water works industry. Ductile cast iron was introduced as an improved alternative to grey cast iron because of its superior ductility and gained immediate industry acceptance because of the brittle nature of grey cast iron, and the misconception that the logarithmically increasing failure rate in grey cast iron water distribution systems was caused by the brittleness of this material.

Unfortunately, ductile iron piping had a much thinner wall than grey cast iron which, in combination with a cosmetic external coating, produced a small-anode/large-cathode corrosion cell between the iron main and copper water services, and resulted in accelerated perforation of the ductile iron at coating defects. The ductile iron corrosion rate was further exacerbated by the increased corrosivity of soils in urban areas due to chlorides from deicing salts permeating to pipe depths.

Cathodic protection provided by magnesium anodes, installed at close intervals along the main by augering, proved to be effective, even on piping lengths that had experienced a high failure rate, as shown in Figure 4. This figure shows the dramatic results achieved on one of the very first applications of sacrificial cathodic protection to water distribution mains in Canada. The piping, which was less than 10 years old, had experienced 22 corrosion failures on about a 500m length and was being considered for replacement when cathodic protection was applied. Sacrificial anodes were re-installed in 1995 after a rise in breaks was observed from 1990-1993, thus extending the service life even further. This technique, dubbed the 'auginode' method as shown in Figure 5, has subsequently been adopted by most major cities in Canada that have been faced with a high failure rate on both grey cast and ductile iron. This has had a tremendous economic impact since water main service life, from a corrosion control viewpoint, can be extended indefinitely as long as new anodes are installed as the existing anodes approach the end of their useful life. Water mains can be cathodically protected for about 5%-10% of their replacement cost. It is estimated that about 200km of iron water piping is being protected annually in Canada using magnesium anodes. Winnipeg is expected to protect about 40km of water distribution piping within the next year using zinc anodes.

Prestressed Concrete Cylinder Pipe

Prestressed concrete cylinder pipe (PCCP) manufactured in accordance with AWWA Standard C301,[10] as shown in Figures 6a and 6b, has been installed in increasing amounts over the last 20 years and is starting to exhibit corrosion failures on the highly stressed reinforcing wire. Because PCCP is large diameter and used for high pressure water transmission service, a corrosion failure can be very disruptive. Corrosion of the prestressing wire is typically caused by ingress of chlorides from the groundwater through the concrete cover to the depth of reinforcing wire where passivity is destroyed when the concentration ratio between the chloride and hydroxyl ion exceeds a threshold value. As the wire thins due to corrosion, the pipe often fails catastrophically when more than one wire is involved. These mains seem to be

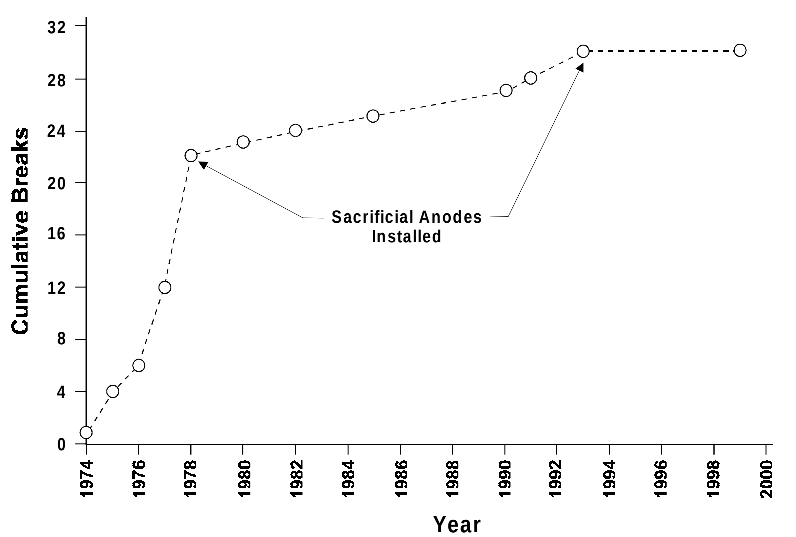

FIGURE 4 • Failure History on a 500m Length of Ductile Iron Piping Before and After the Application of Cathodic Protection

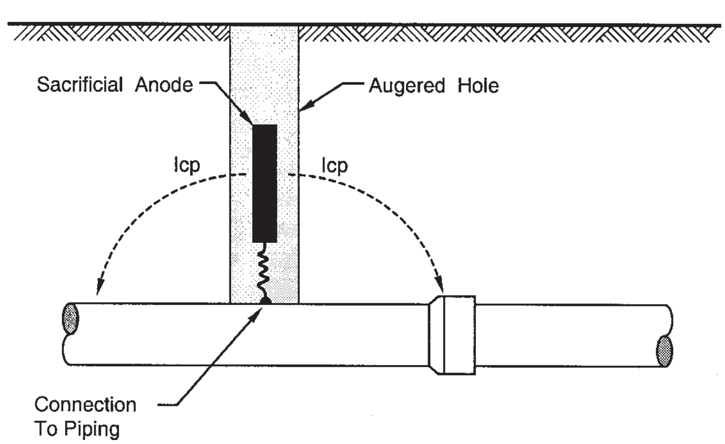

FIGURE 5 • 'Auginode' Cathodic Protection Technique

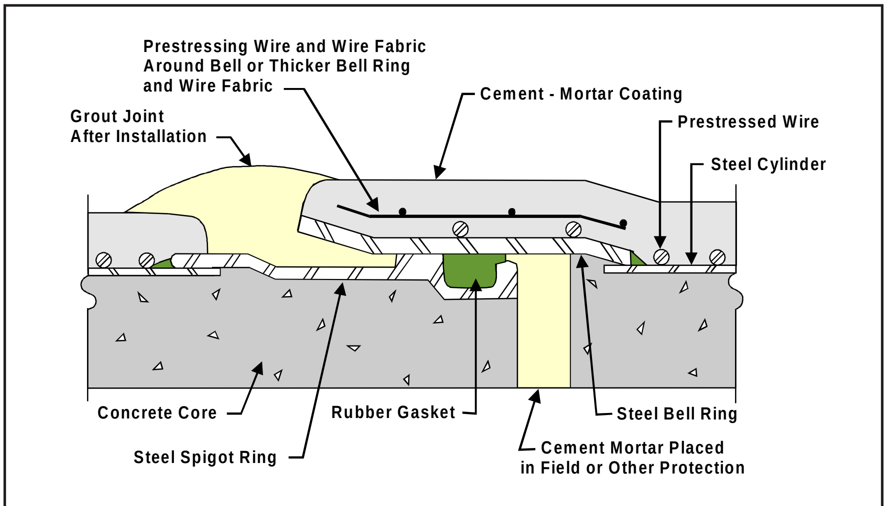

FIGURE 6a • Lined Cylinder Pipe

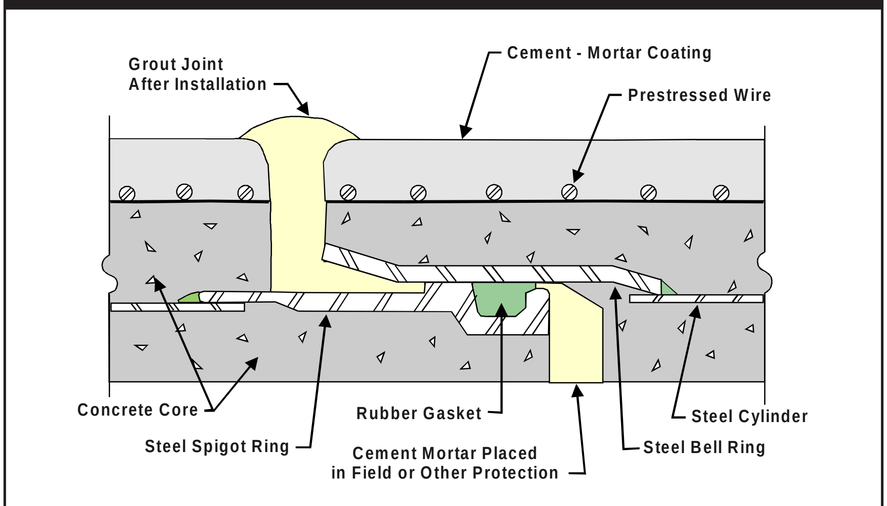

FIGURE 6b • Embedded Cylinder Pipe

particularly susceptible to corrosion attack in soil conditions were the pipe is cyclically wet and dry as would be the case with a fluctuating water table.

Cathodic protection in the form of sacrificial zinc anodes has been shown to be effective in controlling this corrosion[11]. Some concern has been expressed about applying too high a negative potential since the steel reinforcing wires are cold drawn and therefore due to high hardness are subject to hydrogen embrittlement. It has been recommended[12] that the polarized potential be less negative than -970mV$_{cse}$, which generally precludes the use of magnesium anodes (except in high resistivity soils) and impressed current systems. Cathodic protection has typically been recommended for prestressed concrete cylinder pipe[13] with respect to the following conditions:

i) low resistivity soils:

Soil Resistivity (ohm-cm)	
<200	CP is essential
2000 – 3000	CP is recommended
3000 – 10,000	CP not normally required
>10,000	CP not necessary

ii) regions conducive to rapid ground water movement

iii) soils which are very corrosive to concrete

Presently, NACE Task Group T-11-1d is preparing a state-of-the-art document on the criteria for cathodic protection of prestressed concrete elements.

REINFORCED CONCRETE STRUCTURES

Possibly the largest and most expensive corrosion problem in North America is the corrosion of reinforcing steel in bridges and parking structures, especially in coastal regions and in areas where there is generous use of deicing salts on roads. In the USA, the cost of corrosion induced repairs on bridges alone was estimated at $20 billion.[14] Reinforcing steel is normally passive and therefore protected from corrosion when surrounded by concrete whose pore water has a pH in the range of 11-13. However, when chlorides migrate through the concrete cover to the depth of the reinforcing bars and the concentration ratio between the chloride ion and hydroxyl ion exceeds a threshold value, and where there is a ready supply of oxygen, as with atmospherically exposed structures, resulting corrosion of as little as 25mm can cause cracking and consequent spalling of the concrete cover. This is a sight that is familiar to almost everyone. NACE International, in response to this serious corrosion problem, has produced a number of standards[15,16,17] to address this problem.

Bridges

In the 1970's, the Federal Highways Administration in the USA sponsored research into the corrosion control effectiveness of applying cathodic protection to reinforced concrete structures, and in a memorandum issued in 1981 stated that "cathodic protection was the only proven method of controlling corrosion in chloride contaminated concrete bridge decks".[18] A number of different impressed current systems were developed utilizing anodes such as asphalt-coke breeze secondary anode laid over high silicon ion 'pancake' shaped anodes embedded in the bridge deck, a conductive coating applied to the reinforced concrete surface, mixed metal oxide (MMO) coated titanium mesh pinned to the surface, and anode wires laid in saw slots and surrounded by conductive grout. These systems are illustrated in Figures 7a, 7b, 7c and 7d.

It is estimated that over 300 bridges have been cathodically protected in North America over the last 25 years. Cathodic protection technology has also been extended to protecting bridge sub-structures where the most common system consists of a primary anode of thermal sprayed zinc at about 12-20 mils thickness powered by a DC power supply. Attempts to use thermal sprayed zinc as a galvanic anode have encountered difficulties caused by an increase in the zinc-concrete interface resistance and a proportionate decrease in the cathodic protection current output. In England, conductive coatings have been used most frequently for substructure cathodic protection.

Parking Structures

Structural slabs in parking structures typically have less cover over the reinforcing steel than steel in bridge structures, and the concrete is usually of poorer quality, which makes parking slabs particularly susceptible to chloride induced corrosion. Impressed current cathodic protection applied to the soffit side of the slab utilizing a platinum clad wire pinned to the surface and overcoated with a conductive coating, as illustrated in Figure 7b, has been the most frequently used cathodic protection system. By 1990, it was estimated[19] that about half a

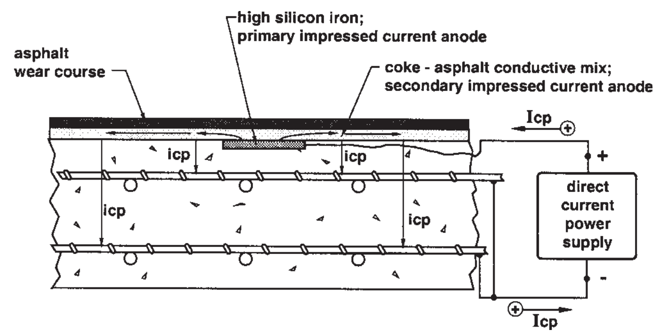

FIGURE 7a • Coke-Asphalt Conductive Mix

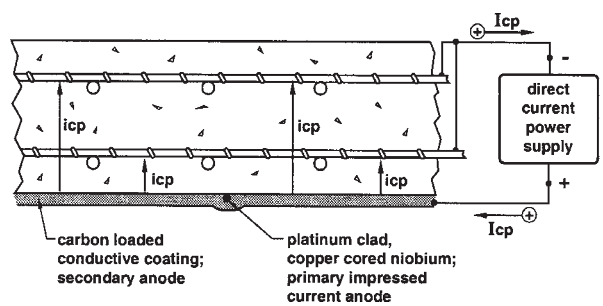

FIGURE 7b • Applied to Soffit

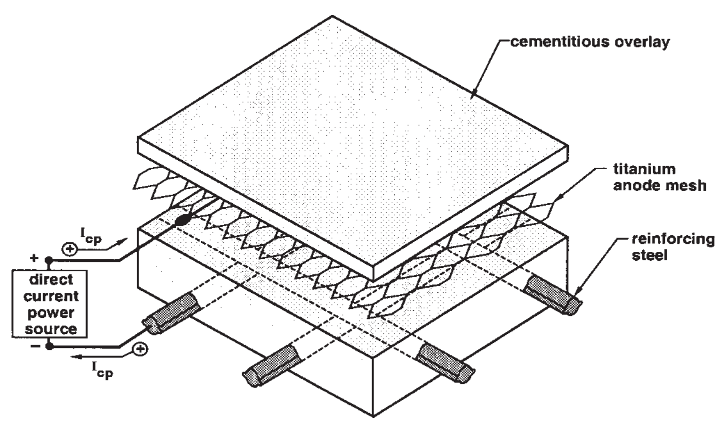

FIGURE 7c • Mixed Metal Oxide Coated Titanium Mesh Pinned to Surface

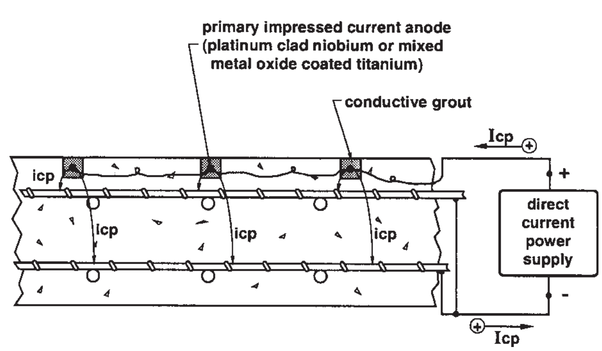

FIGURE 7d • Wire or Ribbon Anodes Place in Saw Slots

million square meters of reinforced concrete parking structure surface had been protected in North America, most of which was by in this method. A guideline specification has also been developed for the conductive coating method.[20]

MISCELLANEOUS APPLICATIONS

Underground Fuel Tanks

It was estimated in 1960,[21] that the typical life of an underground service station tank was only 12 years, due to external corrosion. Led by the gasoline marketing industry, two standards were developed in Canada that involved cathodic protection as a remedy to this problem. One standard addressed existing tanks (as long as the tank systems passed a leak test), which involved the application of impressed current cathodic protection, could be installed in accordance with Guideline Specification #87-1.[22] In addition, a factory installed galvanic protection system, in accordance with CAN/ULC 603.1M Standard,[23] as illustrated in Figure 8, was developed in the 1970's which is now routinely supplied with new coated steel tanks for underground service. Although time limitations have run out for the impressed current standard, steel underground tanks still come equipped with coating and sacrificial anodes, even though most tanks are now double-walled and have an interstitial space that is vacuum monitored to provide an early warning of a leak.

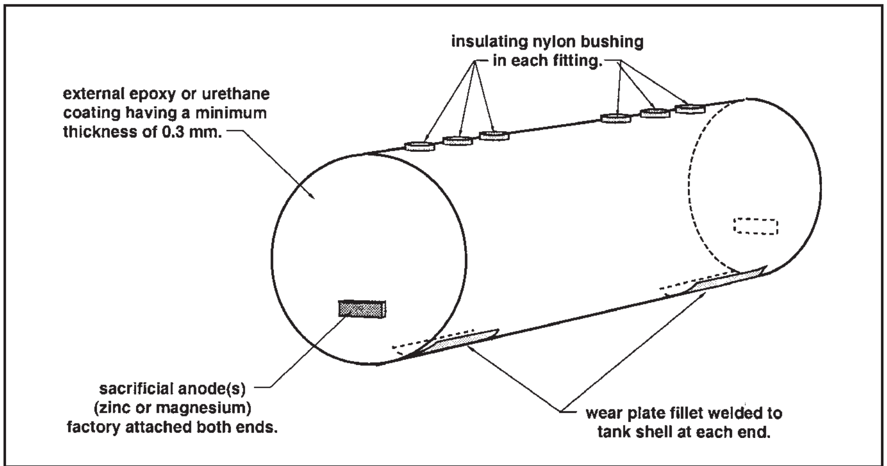

FIGURE 8 • Factory Installed Cathodic Protection System (CAN/ULC-603.1-96)

Effluent Treatment Clarifiers

Steel rake arms of effluent treatment clarifiers often experience accelerated corrosion owing to a corrosive environment coupled with a corrosion cell developed between the rake arm and the reinforcing steel in the floor and wall. For bare or poorly coated rake arms, impressed current as illustrated in Figure 9 has been installed whereas for well-coated structures, sacrificial anodes have been substituted.

Other Applications

To a limited extent, cathodic protection has also been applied to other components of the municipal infrastructure such as hydraulic elevator cylinders, car and truck hoists in service stations, potable water treatment facilities, and swimming pool filters.

SUMMARY

One definition of 'infrastructure' in the Oxford Dictionary[24] is *"roads, bridges, sewers, etc. regarded as a country's economic foundation".* When considering the 'municipal' economic foundation, it is clear that cathodic protection is the most effective method of preserving some important municipal economic assets. With the continued dedication of municipalities to manage their infrastructure more effectively and efficiently, it is ensured that cathodic protection will continue to play a significant role in the future.

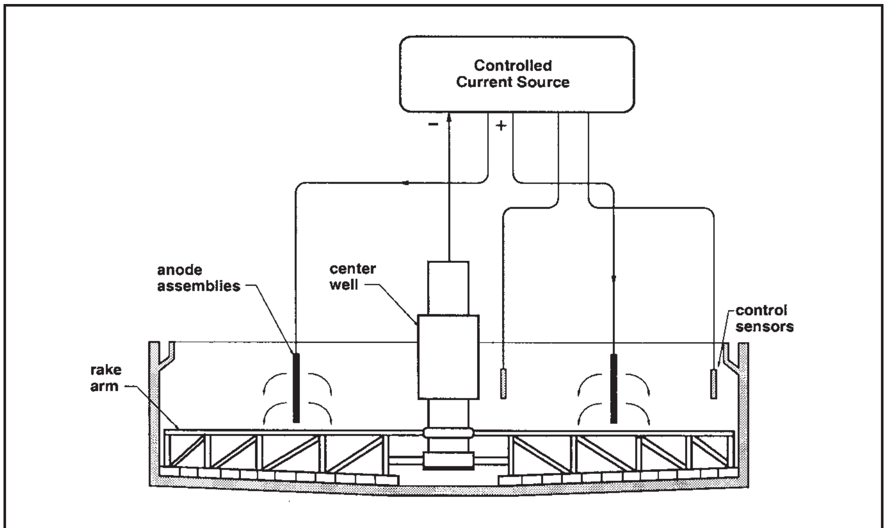

FIGURE 9 • Impressed Current Cathodic Protection to Effluent Treatment Facilities

REFERENCES

1. Davy, H., Philosophical Transactions of the Royal Society, London, 1824-1825.

2. Von Baeckmann, W., and Schwenk, W., Handbook of Cathodic Protection, Portcullis Press Ltd., England, 1975, p11.

3. Kuhn, Robert J., Cathodic Protection of Underground Pipe Lines from Soil Corrosion, API Proceedings, Nov. 1933, Vol. 14, Section 4, p154.

4. Fitzgerald, John, H., Corrosion as a Primary Cause of Cast-Iron Main Breaks, AWWA Journal, Vol. 60, No. 8, Aug. 1968, p887.

5. Bushmann, James G., and Kroon, David H., Cathodic Protection of Water Storage Tanks, AWWA Journal, Vol. 76, No. 1, Jan. 1984, p48.

6. Impressed Current Cathodic Protection of Internal Submerged Surfaces of Steel Water Storage Tanks, NACE Recommended Practice RP0388-95, NACE International, Houston, TX, p3.

7. Galvanic Anode Cathodic Protection of Internal Submerged Surfaces of Steel Water Storage Tanks, NACE Recommended Practice RP0196-96, NACE International, Houston, TX.

8. Impressed Current Cathodic Protection of Internal Submerged Surfaces of Steel Water Storage Tanks, NACE Recommended Practice RP0388-95, NACE International, Houston, TX.

9. AWWA Standard for Automatically Controlled, Impressed-Current Cathodic Protection for the Interior of Steel Water Tanks, ANSI/AWWA D104-97, American Water Works Association, Denver, CO.

10. Prestressed Concrete Pressure Pipe-Steel Cylinder Type for Water and Other Liquids, AWWA Standard C301, American Water Works Association, Denver, CO.

11. Yates, Carl, and Henderson, C., Cathodic Protection of the 48" Dia. C301 Pockwock Transmission Main, NACE Canadian Region Eastern Conference, Nov. 1994.

12. Benedict, Risque L., and Lewis, Richard O., In Search for Criteria to Avoid Embrittlement on Prestressed Concrete Pipe, NACE Corrosion '99 Conference, Paper No. 543.

13. Gouley, J.T., and Moresco, F.E., The Sacrificial Cathodic Protection of Prestressed Concrete Pipelines, NACE Corrosion '87 Conference, Paper No. 318, p2.

14. Broomfield, John, Results of a Field Survey of Cathodic Protection Systems on North American Bridges, NACE Corrosion '92 Conference, Paper No. 204, p1.

15. Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures, NACE Recommended Practice RP0290-90, NACE International, Houston, TX.

16. Design Considerations for Corrosion Control of Reinforcing Steel in Concrete, NACE Recommended Practice RP0187-96, NACE International, Houston, TX.

17. Maintenance and Rehabilitation Considerations for Corrosion Control of Existing Steel-Reinforced Concrete Structures, NACE Recommended Practice RP0390-98, NACE International, Houston, TX.

18. Position on Cathodic Protection Systems, Memorandum, Federal Highways Administration, Washington, D.C., 1981.

19. User's Guide to Cathodic Protection of Reinforced Concrete Parking Structures, National Reinforced Concrete Cathodic Protection Association, Toronto, ON, Oct. 1991, Appendix 'B' and 'C'.

20. Guideline Specification for the Design, Installation, and Evaluation of Conductive Coating Cathodic Protection Systems for Reinforcing Steel in Concrete, National Reinforced Concrete Cathodic Protection Association, Toronto, ON, March 1991.

21. Olive, M.J., Cathodic Protection Used to Control Corrosion of Service Station Underground Equipment, Corrosion, Vol. 16, No. 10, October 1960, p9.

22. Guideline Specification for the Impressed Current Method of Cathodic Protection of Underground Petroleum Storage Tanks, Petroleum Association for Conservation of the Canadian Environment (PACE), Ottawa, 1987.

23. Standard for Galvanic Corrosion Protection Systems for Steel Underground Tanks for Flammable and Combustible Liquids, Underwriters Laboratories of Canada, Toronto, ON, CAN/ULC-S603.1-96, 1996.

24. The Concise Oxford Dictionary, Oxford University Press, New York, NY, 8th Edition, 1990.

ABOUT THE AUTHOR

ROBERT A. GUMMOW is a consulting engineer and President of Correng Consulting Service Inc., a wholly owned subsidiary of Corrosion Service Co. Ltd. He has more than 30 years of experience in the application of CP to a wide variety of structures in many industries. He is a NACE Certificated Corrosion Specialist and has instructed NACE CP courses for more than 20 years. He has a B.S. in electrical engineering.