Metals for Corrosion Resistance: *Part II*

by Catherine Houska

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How long will the metal panels stay attractive? How much maintenance is required? Architects, building owners, structural engineers, and other specifiers regularly face these questions. Materials selection decisions are often based on personal experience and budget limitations rather than scientific data. Usually the result is satisfactory, but when the wrong metal is used and problems arise, reputations can be damaged and remedial costs can be high.

In 1995, the National Institute of Standards and Technology (NIST) estimated the annual cost of metallic corrosion in the United States was \$296 billion, of which \$104 billion was avoidable. Building and construction applications account for 18 percent of this cost.[1]

ADDITIONAL INFORMATION

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Abstract

Predicting a metal's performance in exterior applications, soil, or concrete requires knowledge of the factors influencing corrosion. Unfortunately, good comparative corrosion data for different metals can be difficult to obtain. Research reports comparing service environments and the performance of different metals are usually written by and for metallurgical engineers. This article summarizes published data and other selection criteria so nonmetallurgists can take advantage of available research.

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Atmospheric Corrosion

Atmospheric pollutants, wind-borne marine salt, deicing salt exposure, temperature, humidity, and rainfall must be considered when specifying metals. Sites only a few kilometers apart can have different levels of corrosiveness due to localized pollution and the direction of the prevailing winds.

Moisture from rain, humidity, condensation, or fog must be present for corrosion to occur. Therefore, dry climates tend to be less corrosive. Especially wet climates can also be less corrosive if the design takes advantage of rain's natural cleaning capabilities. When small amounts of regular moisture from very light rain, high humidity, or fog combine with corrosive surface deposits, they can create a highly corrosive, wet film on the surface. Higher temperatures usually accelerate corrosion.

Service Environments

Service environments are classified as rural, urban, industrial, or marine. Within each category, there are high, medium, and low levels of corrosion risk, which are determined by rainfall, air temperature, pollution, and other factors. Future regional development should be considered when evaluating any site.

No two environments are exactly alike. Test data provide general guidelines for sites with similar pollution levels and climates in conjunction with the guidelines in Table 1.

Rural sites have no industrial pollution, coastal atmosphere, or deicing salts. Suburban areas with low population densities and light, nonpolluting industry may be categorized as rural. Migrant industrial pollution can change the classification of sites that otherwise appear rural.

Aluminum alloy 6061 exposed since 1982 about 25 m (82 ft) from the mean high tide.

Urban sites have low to moderate pollution from vehicular traffic and similar sources but may have significant deicing salts. Examples are residential, commercial, and light industrial locations.

Industrial sites have moderate to heavy atmospheric pollution, usually in the form of sulfur and nitrogen oxides from power and chemical process industry plants. Particulate deposits, such as soot or iron oxides, make a site more corrosive.

Coastal and marine sites are exposed to chlorides in airborne salt spray and dry salt particles. Humidity levels determine the potential for corrosion. Salt absorbs moisture at moderate to high humidity levels and can form a corrosive, damp surface film even in normally dry conditions. High salt concentrations combined with high ambient temperatures and moderate humidity create the most

Most Corrosive	Least Corrosive
• High pollution levels, especially sulfur dioxide (SO_2), chlorides, and solid particles • Low to moderate rainfall with moderate to high persistent humidity • Moderate to high temperatures with moderate to high humidity • Frequent, salt-laden ocean fog and low rainfall • Sheltered locations exposed to salt or corrosive pollutants	• Low pollution levels • Low rainfall with low humidity or heavy, frequent rainfall • Low air temperatures, especially extended periods below 0° C (32 °F) • High air temperatures with low humidity

Table 1: Characteristics of the most and least corrosive environments.

TABLES COURTESY THE AUTHOR

aggressive conditions. Generally, sites within 9 km to 18 km (5 mi to 10 mi) of salt water are considered at risk for chloride-related corrosion. Marine atmospheres with aggressive industrial pollution have even higher corrosion potentials.

Deicing salt applied at street level contaminates adjacent soil and is carried surprising distances by road mist and wind. It has been found as high as the twelfth floor of buildings, several hundred feet from busy highways, and in airborne dust year-round. When salt combines with small amounts of moisture from moderate to high humidity, light rain, or fog, a corrosive damp film forms. Sites exposed to deicing salts can be more corrosive than coastal sites because salt concentrations are typically higher. A metal's susceptibility to chloride corrosion and cleaning frequency determines performance.

Sheltered exterior applications, such as building eaves, are potentially more corrosive than boldly exposed applications.[2] Atmospheric dust containing corrosive sulfides, marine salts, deicing salt, iron oxide, and other contaminants may collect in these areas. If sheltered areas are not cleaned regularly to remove this corrosive dust and humidity is moderate to high, there can be corrosion.

Atmospheric Corrosion Tests

Tests comparing metal corrosion performance have been conducted in various service environments around the world.[3,4,5,6,7] The corrosiveness of these test sites is compared using carbon steel calibration samples.[8,9] Calibration sample corrosion rate data for North American test sites are shown in Table 2. Although some of these sites are in regions where deicing salts are regularly used, the samples were not exposed to them.

The data in tables 3 through 6 are from test sites in Japan[10], Panama[11], Kure Beach (North Carolina)[8,12], and South Africa.[13] These data can be used to select appropriate metals for similar

Test Site	Atmosphere	Corrosion rate	
		mils/year	mm/year
United States			
Phoenix, Arizona	Rural arid	0.18	0.005
Point Reyes, California	Marine	19.71	0.500
Waterbury, Connecticut	Industrial	0.89	0.023
Cape Canaveral, Florida	Marine		
0.8 km (0.5 mi) from ocean		3.39	0.086
55 m (180 ft) from ocean			
elevation 18 m (60 ft)		6.48	0.165
elevation 9 m (30 ft)		17.37	0.440
ground level		5.17	0.131
Beach		42.0	1.070
Daytona Beach, Florida	Marine	11.63	0.295
East Chicago, Indiana	Industrial	3.30	0.084
Detroit, Michigan	Industrial	0.57	0.015
Durham, New Hampshire	Rural	1.10	0.028
Kure Beach, North Carolina	Marine		
250 m (800 ft) from ocean		5.73	0.145
25 m (80 ft) from ocean		21.0	0.530
Bayonne, New Jersey	Industrial	3.10	0.079
Cleveland, Ohio	Industrial	1.50	0.038
Middletown, Ohio	Semi-industrial	1.10	0.028
Bethlehem, Pennsylvania	Industrial	1.50	0.038
State College, Pennsylvania	Rural	0.90	0.023
Pittsburgh, Pennsylvania	Industrial	1.20	0.030
Potter County, Pennsylvania	Rural	0.80	0.020
Brazos River, Texas	Industrial marine	3.70	0.094
Canada			
Norman Wells, North West Territory	Polar	0.03	0.001
Montreal, Quebec	Urban	0.90	0.023
Trail, British Columbia	Industrial	1.30	0.033
England			
Dungeness	Industrial marine	19.22	0.490
Pilsey Island	Industrial marine	4.04	0.103
London, Battersea	Industrial	1.80	0.046
Panama			
Miraflores	Tropical marine	1.69	0.043
South Africa			
Durban, Salisbury Island	Marine	2.20	0.056
Durban Bluff	Severe marine	10.22	0.260
Cape Town Docks	Mild marine	1.84	0.047
Walvis Bay military base	Severe marine	4.33	0.110

Table 2: Corrosion rates of carbon steel calibrating samples at various test sites.

Anodized aluminum exposed since 1942.

Material	Pacific Coast		Sea of Japan, Coastal	Inland		Industrial	
City	**Omaezaki**	**Makurazaki**	**Wajima**	**Takayama**	**Obihiro**	**Kawasaki**	**Tokyo**
Type 304	0.003 (0.00008)	0.006 (0.00015)	0.0035 (0.00009)	0.0055 (0.00014)	0.0059 (0.00015)	0.033 (0.00084)	0.037 (0.00093)
Aluminum	0.157 (0.004)	0.118 (0.003)	0.118 (0.003)	0.071 (0.0018)	0.122 (0.0031)	2.421 (0.0615)	0.118 (0.003)
Weathering steel	30.12 (0.765)	20.63 (0.524)*	19.29 (0.490)	14.094 (0.358)	14.45 (0.367)*	72.24 (1.835)	44.13 (1.121)
Carbon steel	41.42 (1.052)	32.05 (0.814)	27.68 (0.703)	19.21 (0.488)	16.97 (0.431)	156.81 (3.983)	70.75 (1.797)

* Samples exposed for four years.

Table 3: Average corrosion weight loss mils/year (mm/year) at four Japanese sites after four or five years exposure.

environments in North America and for developing life cycle cost analyses.

Corrosion in Soil

Many factors contribute to the corrosiveness of soils including soil type, texture, permeability, mineral composition, climate, moisture content, water table position, resistivity, soluble ion content, microbes, oxygen reduction potential, and soil pH. Typically, the most corrosive soils are those with the lowest pH, highest chloride and sulfate levels, and poor drainage. Soil probes are often used to assess soil corrosion potential.

Cast iron has provided 100-year service in many soils, but soils with high concentrations of decomposing organic matter; alkalis; salt; and mining, industrial, and municipal wastes can corrode cast iron. Several studies have shown an increase in corrosion-related leaks of cast iron pipe since the 1960s, often associated with an increased use of deicing salts. The most important factors identified in these studies were resistivity, chloride levels, and stray currents.[14]

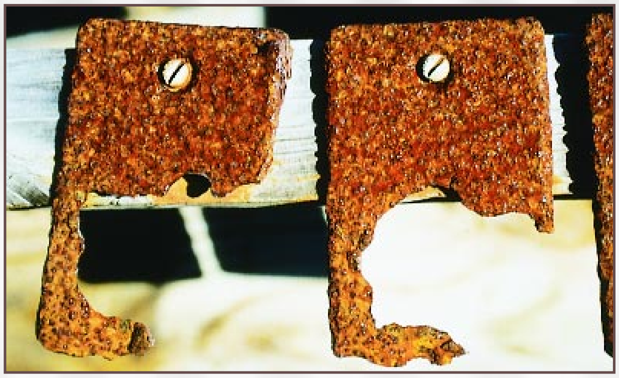
Cathodic protection and coatings can prevent external corrosion of buried steel structures, but coating damage, deterioration, defects, or the absence of effective cathodic protection can cause failures. Deterioration is most common in soils with high clay levels, soil movement, or settling. High temperatures or excessive cathodic protection can also accelerate coating deterioration.

NIST has tested unprotected stainless steels in a variety of soils. Both types 304 and 316 are highly resistant to pitting and general corrosion in most soils. In highly aggressive soils, such as those with high chloride levels, Type 304 was susceptible to pitting corrosion, but Type 316 showed good resistance to corrosion in all test soils including tidal marsh and clay. Type 316 only experienced pitting in oceanfront sand flooded by seawater.[15]

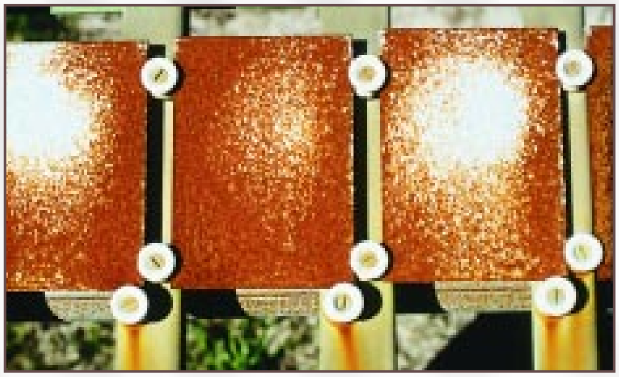
Metal Embedded in Concrete

There is growing interest in extending the service life of concrete structures. The U.S. Office of Technology Assessment recognizes corrosion-related, steel-reinforced bridge deck deterioration as a "serious national problem."[16] In the United States, over 5,000 bridges are built or rebuilt every year and over 200,000 are in serious condition.[17] Numerous field and laboratory tests of metal rebar have been sponsored by state and national highway transportation departments in Europe, Canada, and the United States.

Wiss, Janney, Elstner Associates, Inc., conducted a five-year study for the U.S. Federal Highway Administration to identify a reinforcement bar material that would not require a corrosion-related



Coated (60 Zn, 20 Al, 20 Mg) carbon steel exposed since 1952.

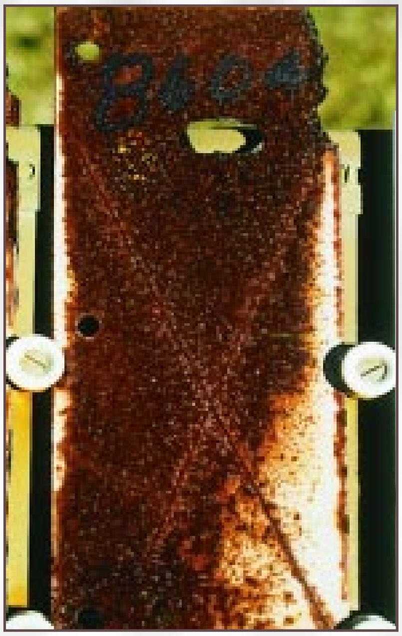


Bare G-90 galvanized steel exposed since 1981.

Constituent mg/10m^3	Cristobal (coastal)			Miraflores (Inland)		
	Max.	Min.	Avg.	Max.	Min.	Avg.
Total dissolved solids	19.35	1.06	2.47	9.11	0.53	3.04
Organic & volatile matter	6.07	0.56	2.61	2.44	0.39	1.20
Sulfate	2.26	0.11	0.71	3.99	0.04	0.88
Chloride	1.48	0.12	0.81	0.56	0.05	0.19
Nitrate	0.39	0.00	0.11	0.42	0.00	0.14
Metal	**Avg. metal loss after 16 years, mils (mm)**	**Avg. annual corrosion rate, mils/year (mm/year)**	**Deepest pit, mils (mm)**	**Avg. metal loss after 16 years, mils (mm)**	**Avg. annual corrosion rate, mils/year (mm/year)**	**Deepest pit, mils (mm)**
Type 316 stainless steel	<0.01 (<0.0003)	<0.01 (<0.0003)	<4.92 (<0.125)	0 (0)	0 (0)	<4.92 (<0.125)
Aluminum 6061-T6	0.11 (0.0028)	<0.01 (0.0003)	<4.92 (<0.125)	0.06 (0.0015)	<0.01 (<0.0003)	<4.92 (<0.125)
Nickel-silver	0.37 (0.0094)	0.02 (0.0005)	<4.92 (<0.125)	0.28 (0.0071)	0.02 (0.0005)	<4.92 (<0.125)
Cast bronze	0.79 (0.020)	0.02 (0.0005)	5.98 (0.152)	0.39 (0.0099)	<0.01 (<0.0003)	32.99 (0.838)
Copper (99.9%)	0.79 (0.020)	0.03 (0.0008)	<4.92 (<0.125)	0.26 (0.0069)	<0.01 (<0.0003)	<4.92 (<0.125)
Lead (99%)	0.79 (0.020)	0.05 (0.0013)	<4.92 (<0.125)	0.55 (0.014)	0.04 (0.001)	<4.92 (<0.125)
Low alloy steel	7.80 (0.198)	0.04 (0.001)	17.01 (0.432)	5.67 (0.144)	0.28 (0.007)	22.01 (0.559)
Cast gray iron	7.72 (0.196)	0.32 (0.0081)	37.01 (0.940)	5.94 (0.151)	0.28 (0.007)	37.01 (0.940)
Cast iron (18% Ni)	9.17 (0.233)	0.59 (0.015)	59.02 (1.499)	2.91 (0.074)	0.24 (0.006)	9.02 (0.229)
Carbon steel	10.63 (0.270)	0.47 (0.012)	39.02 (0.991)	8.58 (0.218)	0.43 (0.011)	25.98 (0.660)
Wrought iron	18.70 (0.475)	0.94 (0.024)	60.98 (1.549)	12.20 (0.310)	0.63 (0.016)	37.01 (0.9400)

Table 4: Atmospheric corrosion data from a 16-year U.S. Naval Research Laboratory study at two sites in Panama.

repair for 75 years to 100 years. They tested black bars, epoxy-coated bars, stainless steel, copper-clad steel, galvanized steel, and spray metallic clad steel. The corrosion rate of Type 316 stainless steel was 800 times lower than that of black bar. They concluded Type 316 should be considered for installations where corrosion induced damage is difficult or costly to repair, such as parking garages, sea walls, piers, tunnels, and bridges with high traffic volumes.[18] The results of other studies have been similar.



Painted cold rolled steel exposed since 1988.

Depending on bridge size and complexity, stainless-steel rebar increases the initial project cost between 1 percent and 20 percent. When repair and disruption costs are considered, stainless steel provides substantial life cycle cost savings over a 100-year period in applications with chloride exposure.

Conclusion

The specifier's challenge is to select a metal and surface finish that will continue to meet a client's functional and aesthetic requirements for 20, 50, or even 100 years. Careful site evaluation and a review of available corrosion data must be considered along with project cost restrictions, life cycle costs, required service life, maintenance, and appearance expectations. Industry associations, metal producers, and corrosion specialists can be of great assistance throughout this process.

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High strength low alloy weathering steel exposed since 1968.

Metal	Exposure time, years	Avg. corrosion rate, mils/year (mm/year)
Type 316 stainless steel	15	<0.001 (<0.000025)
Type 304 stainless steel	15	<0.001 (<0.000025)
Galvalume	13	0.33 (0.0084)
Galvanized steel	13	0.68 (0.0173)
Carbon steel	16	5.8 (0.147)

Table 5: Average corrosion rates 250 m (800 ft) from mean high tide at Kure Beach, North Carolina.

Information Sources

Additional information can be obtained from the following industry associations:

Aluminum Association Inc.
(202) 862-5100
http://www.aluminum.org

American Iron and Steel Institute
(202) 452-7100
www.steel.org

Copper Development Institute
(212) 251-7200
www.copper.org

Nickel Development Institute (stainless steel and nickel alloys)
(416) 591-7999
http://www.nidi.org

Specialty Steel Industry of North America (stainless steel)
(202) 982-0355 or (800) 982-0355
www.ssina.com

Captions:

The atmospheric corrosion test samples shown in the photos are at the LaQue Center for Corrosion Technology, Inc., an internationally respected corrosion research facility in Kure Beach, North Carolina. The samples have been exposed to the elements and are only cleaned by rain. Except where noted, the samples are 250 m (820 ft) from the ocean's mean high tide.

These Statue of Liberty corrosion demonstration panels have been in place since 1984. Type 316 and carbon steel plate samples were attached to copper sheets with a saddle which is riveted in place. (Page 23, left photo) Type 316 stainless steel and copper combination is performing well. (Page 23, right photo) The mild steel plate's corrosion product has expanded and broken the copper saddle.

Type 304 exposed since 1941.

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4 Chandler, K. A. *Stainless Steels for Decorative Uses in Architecture*. I.S.I. Publication No. 117, 1969.

5 Karlsson, A. and Olsson, J. *Atmospheric Corrosion of Stainless Steels*. Byggmastaren, 10, pages 71–86, 1976.

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8 Heidersbach, Robert H., *Marine Corrosion*, Metals Handbook Ninth Edition, Volume 13 Corrosion, ASM International, pages 893–918.

9 Slater, John E., *Corrosion in Structures*, Metals Handbook Ninth Edition, Volume 13, Corrosion, ASM International, page 1300.

10 *Technical Manual for the Design and Construction of Roofs of Stainless Steel Sheet*, NiDI publication No. 12 006, Japanese Stainless Steel Association, and the Nickel Development Institute, 1989.

11 Southwell, C.R. and Bultman, J.D., *Atmospheric Corrosion Testing in the Tropics*, Atmospheric Corrosion, published by J. Wiley & Sons, pages 943–967, 1982.

12 *Galvalume Sheet Steel Spec-Data Sheet*, Bethlehem Steel Corporation, August, 1992.

13 Callaghan, B.G., *Atmospheric Corrosion Testing in Southern Africa: Results of a twenty year national exposure programme*, Division of Materials Science and Technology, CSIR.

Type 316 exposed since 1941.

	Pretoria-CSIR	Durban Bay	Cape Town Docks	Durban Bluff	Walvis Bay	Sasolburg
Environment						
Location Type	rural, pollution	pollution moderate pollution	marine, moderate pollution	severe marine, moderate/low pollution	severe marine, low pollution	industrial, high pollution
SO$_2$ Range µg/m^3	6 – 20	10-55	19 – 39	10 – 47	NA	NA
Fog Days/year	NA	NA	NA	NA	113.2	NA
Avg. rainfall, in/year (mm/year)	29.4 (746)	40 (1,018)	20 (508)	40 (1,018)	0.31 (8)	26.7 (677)
Relative Humidity Range%	26 - 76	54 - 84	52 - 90	54 - 84	69 - 96	49 - 74
Temp. range F (C)	43 – 79 (6 – 26)	61 – 80 (16 – 27)	48 – 77 (9 – 25)	61 – 80 (16 – 27)	50 – 68 (10 – 20)	41 – 67 (5 – 20)
Unpainted galvanized steel life, years*	5 - 15	3 - 5	3 - 7	3 - 5	0.6 - 2	5 - 15
Annual Corrosion Rate mils/year (mm/year)						
Stainless Steels						
Type 316	<0.001 (0.000025)	<0.001 (0.000025)	0.001 (0.000025)	0.01 (0.000279)	0.004 (0.000102)	NA
Type 304	<0.001 (0.000025)	0.003 (0.000076)	0.005 (0.000127)	0.02 (0.000406)	0.004 (0.000102)	NA
Type 430	<0.001 (0.000025)	0.02 (0.000406)	0.01 (0.000381)	0.07 (0.001727)	0.020 (0.000559)	0.004 (0.000107)
Aluminum Alloys						
AA 93103	0.01 (0.00028)	0.21 (0.00546)	0.17 (0.00424)	0.77 (0.01946)	0.18 (0.00457)	0.11 (0.00281)
AA 95251	0.01 (0.00033)	0.14 (0.00353)	0.15 (0.00371)	0.66 (0.01676)	0.16 (0.00417)	NA
AA 96063	0.01 (0.00028)	0.12 (0.00315)	0.14 (0.00366)	0.79 (0.020)	0.19 (0.00495)	NA
Copper	0.22 (0.00559)	0.37 (0.0094)	0.28 (0.00711)	0.97 (0.0246)	1.51 (0.0384)	0.55 (0.014)
Zinc	0.13 (0.0033)	0.91 (0.0231)	1.14 (0.029)	4.37 (0.111)	NA	0.60 (0.0152)
COR-TEN®	0.90 (0.0229)	8.35 (0.212)	3.60 (0.0914)	31.89 (0.810)	45.28 (1.150)	4.21 (0.107)
Mild steel	1.70 (0.0432)	14.61 (0.371)	10.12 (0.257)	86.22 (2.190)	33.31 (0.846)	5.91 (0.150)

Galvanized steel life = defined as red rust on 5% of the surface area

NA = data was not available for this site

Table 6: Average annual corrosion rate after 20 years exposure in South Africa.

Zinc tin alloy exposed since 1960 about 25 m (82 ft) from the mean high tide.

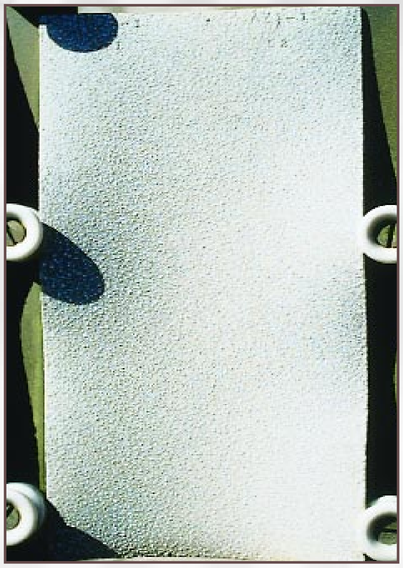
14 Palmer, J.D., *Environmental Characteristics Controlling the Soil Corrosion of Ferrous Piping*, Effects of Soil Characteristics on Corrosion, ASTM STP 1013, 1989.

15 W. Gerhold and B. Sanderson, *Corrosion Behavior of Some Stainless steels in Underground Soil Environments*, Chemical Stability and Corrosion Division, National Bureau of Standards, Washington, D.C.

16 OTA (1987). Office of Technology Assessment Staff Paper, Construction and Meterials Research and Development for the Nation's Public Works, Chapter 7, Recent Materials Developments—Anticorrosion Methods.

17 G. Frohnsdorff, T.J. Pasko, ASTM Standardization News 27, 1, page 20 (1999).

18 D. McDonald and D. Pfeifer, Wiss, Janney, Elstner Associates, Inc. and P. Virmani, Federal Highway Administration, *Corrosion-resistant Reinforcing Bars Findings of a 5-Year FHWA Study*.



Pure zinc exposed since 1960 about 25 m (82 ft) from the mean high tide.

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