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Atmospheric Corrosion

ENVIRONMENTAL POLLUTANTS CAUSING CORROSION

Pollutant	Sources	Susceptible Metals
Sulfur Dioxide (SO_2)	Fossil fuel combustion, petrochemical industries, pulp and paper industry, metal producing industry	Most metals
Nitrogen Dioxide (NO_2)	Auto & truck emissions, fossil fuel combustion, various industries	Copper, brass, synergistic with SO_2
Hydrogen Sulfide (H_2S)	Pulp & paper industries, chemical industry, sewage plants, garbage dumps, oil refineries, animal shelters, volcanic activity, swamp areas, marine tidal areas	All copper and silver based metals
Chlorine (Cl_2) but most important is chlorine containing gases.	Bleaching plants in industries, metal production, PVC plants, cleaning agents	Most metals synergistic with other pollutants
Ammonia and Its Salts (NH_3 and NH^+_4)	Fertilizer, animal and human activity, detergents	All copper based alloys, nickel, silver
Chloride (Cl^-)	Sea salt mist, road salt areas	Most metals
Soot (Carbon)	Combustion, auto & truck emissions, steel production	Synergistic with other pollutants; provides cathodic sites for most metals

Pollutant	Sources	Susceptible Metals
Ozone	Formed in polluted areas, highest concentrations in smog	Strong oxidant to produce acids which attack most metals
Mineral Acids (H_2SO_4, HCl, HF, HNO_3)	Pickling industry, chemical industry, metals production, semiconductor industry	Most metals, glass, ceramics
Organic acids	Wood, packing material, animals, preservatives	Long-term effects on some metals

Source: Manual 20, *Corrosion Tests and Standards: Application and Interpretation* (West Conshohocken, PA, USA: ASTM International, 1995), p. 638. Reprinted with permission, copyright ASTM.

CLASSIFICATION OF TEST STIES ACCORDING TO ISO 9223 ENVIRONMENTAL CRITERIA

SO_2 pollution			pollution by airborne salinity			time of wetness		
test site	average value	cate-gory	test site	average value	cate-gory	test site	average value	cate-gory
Dirkenes	1.2	P0	Svanwik	1.0	S0	Oymyakon	381	T3
Tannanger	4.0	P0	Batumi	1.0	S0	San Juan	855	T3
Ahtari	4.1	P0	Oslo	2.1	S0	Boucherville	1396	T3
El Pardo	4.9	P0	Otaniemi	2.5	S0	Madrid	2060	T3
Kattesand	5.0	P0	Helsinki	3.7	S0	Tokyo	2173	T3
Kvarnvik	5.0	P0	Tokyo	4.4	S0	Kopisty	2444	T3
Murmansk	5.0	P0	Picherande	6.5	S1	Svanwik	2605	T4
Oymyakon	5.0	P0	Bergen	7.1	S1	Oslo	2641	T4
Choshi	7.7	P0	Borregaard	8.2	S1	Jubay-Antarct	2693	T4
Bergen	8.6	P0	Stratford	15.1	S1	Lagoas	2840	T4
Picherande	9.1	P0	Auby	16.0	S1	Praha	2991	T4
Kure Beach	9.6	P0	Vladivostok	18.4	S1	Ahtari	3105	T4
Stockholm V.	9.8	P0	Murmansk	19.9	S1	Paris	3189	T4
Okinawa	11.1	P0	Lagoas	21.2	S1	Kasperské H.	3206	T4
Oslo	13.8	P1	Saint Denis	27.8	S1	Batumi	3216	T4
Tokyo	14.6	P1	Baracaldo	29.2	S1	El Pardo	3223	T4
Otaniemi	15.3	P1	Boucherville	59.0	S1	Murmansk	3227	T4
Boucherville	15.9	P1	Choshi	66.8	S1	Otaniemi	3256	T4
Svanwik	16.7	P1	Kattesand	85.5	S1	Salins de Gir.	3310	T4
Kasperské H.	17.1	P1	Okinawa	130.0	S2	Borregaard	3339	T4
Bergisch G.	18.0	P1	Ostende (B)	173.0	S2	Helsinki	3578	T4
Helsinki	18.9	P1	Salind de Gr.	184.0	S2	Ponteau M.	3846	T4
Stratford	19.9	P1	Kure Beach	184.0	S2	Okinawa	3852	T4
Saline de Gir.	20.0	P1	Biarritz	193.0	S2	Vladivostok	3920	T4
Los Angeles	20.0	P1	Ponteau Mart.	241.0	S2	Los Angeles	4003	T4
Rve	21.2	P1	Rye	300.0	S2	Picherande	4171	T4
Ostende (B)	24.0	P1	Tannanger	321.0	S2	Picherande	4171	T4
Batumi	25.8	P1	St. Remy	378.0	S2	Bergisch G.	4267	T4
Vladivostok	28.6	P1	Panama	619.0	S3	Saint Denis	4268	T4
St. Remy	30.3	P1	Kvarnvik	667.0	S3	Kure Beach	4289	T4
Baracaldo	32.1	P1	Iugazu	no data		Baracaldo	4375	T4
Borregaard	44.2	P2	Camet	no data		Bergen	4439	T4
Madrid	44.2	P2	Buenos Aires	no data		Auby	4571	T4
Lagoas	48.7	P2	San Juan	no data		Tannanger	4583	T4
Saint Denis	49.6	P2	Jubay-Antarct.	no data		Buenos Aires	4645	T4
Panama	51.5	P2	Kasperské H.	no data		Iguazu	5680	T5

SO_2 pollution			pollution by airborne salinity			time of wetness		
test site	average value	category	test site	average value	category	test site	average value	category
Paris	53.4	P2	Praha	no data		Choshi	5704	T5
Praha	67.5	P2	Kopisty	no data		Stratford	5783	T5
Ponteau M.	87.0	P2	Bergisch G.	no data		Ostende (B)	6083	T5
Kopisty	89.9	P2	Ahtari	no data		Camet	6088	T5
Auby	188.0	P3	Paris	no data		St. Remy	6310	T5
Biarritz	no data		Judgeford	no data		Panama	7598	T5
Buenos Aires	no data		Birkenes	no data		Biarritz	no data	
Camet	no data		Madrid	no data		Judgeford	no data	
Crowthorne	no data		El Pardo	no data		Stockholm V.	no data	
Fleet Hall	no data		Stockholm V.	no data		Kattesand	no data	
Iugazu	no data		Crowthorne	no data		Kvarnvik	no data	
Judgeford	no data		Fleet Hall	no data		Crowthorne	no data	
Newark	no data		Newark	no data		Rye	no data	
Point Reyes	no data		Res. Tri. Park	no data		Fleet Hall	no data	
Res. Tri. Park	no data		Point Reyes	no data		Newark	no data	
San Juan	no data		Los Angeles	no data		Res. Tri. Park	no data	
Jubay-Antarct.	no data		Oymyakon	no data		Point Reyes	no data	

Source: D. Knotkova, K. Kreislova, S.W. Dean, Jr., eds., *ISOCORRAG International Atmospheric Exposure Program: Summary of Results* (West Conshohocken, PA, USA: ASTM International, 2010), p. 41.

METALS USED IN THE ISOCORRAG PROGRAM

- Carbon Steel: unalloyed carbon steel (Cu 0.03% to .10%, P < 0.07%) (e.g. UNS G10060 British Steel composition below, EN 10130)
- Zinc: min. 98.5% (e.g. UNS Z18002, EN 1179)
- Copper: min. 99.5% (e.g. UNS C1100 flat panels, UNS C 10200 wire helices, EN 1652)
- Aluminum: min. 99.5% (e.g. UNS A91100, EN 485)

COMPOSITION OF UNALLOYED CARBON STEEL USED IN THE COLLABORATIVE PROGRAM

alloying element	percentage
carbon	0.056
silicon	0.060
phosphorus	0.012
chromium	0.020
molvbdenum	0.010
nickel	0.040
copper	0.030
niobium	0.010
titanium	0.010
vanadium	0.010
aluminum	0.020
tin	0.005
nitrogen	0.004
manganese (X-ray florescence)	0.390

Source: D. Knotkova, K. Kreislova, S.W. Dean, Jr., eds., *ISOCORRAG International Atmospheric Exposure Program: Summary of Results* (West Conshohocken, PA, USA: ASTM International, 2010), p. 7.

CORROSION LOSSES OF STEEL (µM)—1, 2, 4, AND 8 YEARS OF EXPOSURE

Code	Testing Site	flat specimens				helix specimens			
		1 year	2 years	4 years	8 years	1 year	2 years	4 years	8 years
ARG 1	Iugazu	5.8	10.1	11.1		9.2	15.4	18.0	
ARG 2	Camet	45.2	46.1	123.2		77.1	101.0	168.4	
ARG 3	Buenos Aires	14.7	26.6			25.1	29.8	51.6	
ARG 4	San Juan	4.6	6.2			7.4	7.6		
ARG 5	Jubay-Antarct.	38.1	50.0			62.9	51.2		
CND 1	Boucherville	24.0	32.7	31.1	55.2	26.7	40.9	71.2	55.2
CS 1	Kasperské Hory	26.0	35.5	51.5	65.6	47.6	71.9	110.0	107.2
CS 2	Praha-Bèchovice	47.4	76.2	88.9	131.2	65.0	115.0	175.2	161.6
CS 3	Kopisty	70.7	108.0	111.0	166.4	108.0	175.0	272.0	263.2
D 1	Bergisch Glad.	36.2	50.8		98.4	52.1	74.8		122.4
SF 1	Helskinki	33.3	60.0	82.0	103.2	42.7	74.4	97.2	139.2
SF 2	Otaniemi	25.6	43.8	58.8	73.6	36.2	63.8	73.6	111.2
SF 3	Ahtari	12.8	24.8	34.8	44.8	16.1	31.8	42.4	56.8
F 1	Saint Denis	37.2	59.6	79.3	106.4	49.6	78.3	108.4	
F 2	Ponteau Mart.	72.4	121.0	179.6	284.0	123.5	192.0	219.6	
F 3	Picherande	16.1	29.4	32.7		22.8	36.8	43.6	
F 4	St. Remy	43.1	84.4	102.0	147.2	94.7	103.2	198.8	
F 5	Salins de Gir.	73.0	117.2	221.2	288.8	132.0	169.0		
F 6	Ostende (B)	99.3	187.0	304.0		130.0	181.0		
F 7	Paris	41.7	67.4	123.0	176.0	51.7	105.0	122.0	
F 8	Auby	106.3	150.0	227.2	318.0	145.0	288.0	370.0	
F 9	Biarritz	87.4	120.2	157.6		67.9	93.5	116.0	
JAP 1	Choshi	43.3	68.2	125.0	216.0	93.7	163.0	284.0	
JAP 2	Tokyo	39.5	59.8	91.2	126.4	39.1	47.0	63.6	
JAP 3	Okinawa	75.2	202.0	376.0		109.0	239.0	337.0	
NZ 1	Judgeford	19.0	28.8			35.8	45.2		
N 1	Oslo	25.2	41.2	49.2	57.6	35.0	53.2	70.0	68.4
N 2	Booregaard	61.7	103.0	134.0	170.4	90.9	135.0	227.0	271.8
N 3	Birkenes	19.7	37.8	52.8	60.6	27.0	50.4	68.4	75.6
N 4	Tannanger	59.6	84.4	121.0	148.2	74.1	103.0	161.0	160.8
N 5	Bergen	27.9	39.8	56.4	63.0	32.8	47.0	68.4	76.2
N 6	Svanwik	20.2	33.8	46.8	54.6	29.0	47.4	67.4	78.6
E 1	Madrid	27.7	42.6	44.8	53.1	29.3		59.6	64.8
E 2	El Pardo	15.5	28.2	35.6	43.2	21.6		46.0	

Code	Testing Site	flat specimens				helix specimens			
		1 year	2 years	4 years	8 years	1 year	2 years	4 years	8 years
E 3	Lagoas	26.9	48.6	68.4	95.2	35.9		74.8	104.0
E 4	Baracaldo	43.9	66.8	77.2	103.2	56.0		107.2	147.2
S1	Stockholm Vanadis	24.4	40.8	54.4	66.4	41.5	77.0	101.0	172.0
S 2	Kattesand	35.2	54.0	80.3	115.2	60.8	92.4	151.0	285.6
S 3	Kvarnvik	61.6	79.4	110.0	148.0	67.7	107.0	159.0	280.0
UK 1	Stratford	38.7	62.6	82.3		50.3	94.5	132.4	
UK 2	Crowthorne	37.4	62.2	79.3		57.9	91.4	128.4	
UK 3	Rye	58.5	90.8	114.0		92.5	174.0	240.0	
UK 4	Fleet Hall	39.0	65.3	91.2		56.9	67.0	155.0	
US 1	Kure Beach	37.9			189.5	81.8			831.2
US 2	Newark	26.4			65.6	27.3			82.4
US 3	Panama	373.0				297.0	870.0		
US 4	Res. Tri. Park	23.1							
US 5	Point Reyes	36.8	55.0		126.4	147.0	244.0		
US 6	Los Angeles	21.4	24.8		57.6	19.2			
SU 1	Murmansk	31.3	44.4	80.0		51.7	71.8	104.0	
SU 2	Batumi	28.7	41.4	52.8		28.7	39.8	50.4	
SU 3	Vladivostok	25.9	48.2	82.4		66.8	153.0	244.0	
SU 4	Oymyakon	0.8	2.1	4.0		1.9	3.3	6.4	

Source: D. Knotkova, K. Kreislova, S.W. Dean, Jr., eds., *ISOCORRAG International Atmospheric Exposure Program: Summary of Results* (West Conshohocken, PA, USA: ASTM International, 2010), p. 34.

CORROSION LOSSES OF ZINC (μM) 1, 2, 4, AND 8 YEARS OF EXPOSURE

Code	Testing Site	flat specimens				helix specimens			
		1 year	2 years	4 years	8 years	1 year	2 years	4 years	8 years
ARG 1	Iugazu	1.36	3.48	3.64		1.94	1.70	2.68	
ARG 2	Camet	1.98	3.48	3.64		3.79	1.70	2.68	
ARG 3	Buenos Aires	1.00	1.74	3.20		1.52	2.70	4.84	
ARG 4	San Juan	0.19	0.30	1.24		1.01			
ARG 5	Jubay-Antarct.	1.65	2.14			3.00	4.94		
CND 1	Boucherville	1.40	2.48	4.96	8.88	2.00	3.12	6.48	12.72
CS 1	Kasperské Hory	1.90	2.38	3.77	6.88	2.20	3.56	4.92	9.76
CS 2	Praha-Bèchovice	2.80	3.62	6.61	11.68	3.30	5.41	10.20	36.16
CS 3	Kopisty	3.50	8.38	15.60	26.88	4.75	8.93	18.30	12.88
D 1	Bergisch Glad.	1.60	2.64		7.20	1.80	3.28		10.88
SF 1	Helskinki	1.30	2.40	4.40	7.28	2.32	4.80	8.00	14.16
SF 2	Otaniemi	0.90	1.60	2.80	4.16	1.80	2.40	4.00	6.16
SF 3	Ahtari	0.70	1.20	1.60	2.64	1.20	1.80	2.00	3.04
F 1	Saint Denis	1.50	2.80	4.90	9.92	3.51	8.10	10.24	
F 2	Ponteau Mart.	2.65	4.00	7.90	16.24	14.50	20.80	28.40	
F 3	Picherande	0.90	1.80	2.40		2.20	4.10	3.80	
F 4	St. Remy	1.50	2.80	4.50	8.56	4.01	5.30	8.72	
F 5	Salins de Gir.	4.55	7.80	11.40	13.44	5.70	9.80		
F 6	Ostende (B)	5.10	5.78	10.30		10.60	11.10		
F 7	Paris	3.00	4.50	6.20	9.76	2.80	6.60	7.70	
F 8	Auby	5.60	10.72	21.88	34.40	8.50	15.24	28.00	50.72
F 9	Biarritz	4.30	6.67	12.48		7.13	11.80	31.52	
JAP 1	Choshi	1.40	2.60	5.20	9.00	2.80	4.40	8.80	
JAP 2	Tokyo	1.50	2.20	4.00	8.00	1.50	2.80	6.00	
JAP 3	Okinawa	3.40	9.00	10.00		8.80	15.80	33.20	
NZ 1	Judgeford	0.66	1.68			1.08	3.40		
N 1	Oslo	1.25	2.60	4.12		1.80	3.60	5.60	
N 2	Booregaard	3.80	7.00	13.20		5.70	10.60	19.50	
N 3	Birkenes	2.30	3.00	5.16		2.00	3.40	3.56	
N 4	Tannanger	3.00	6.60	9.80		3.30	5.20	9.84	
N 5	Bergen	2.10	1.80	8.30		2.20	2.80	5.50	
N 6	Svanwik	0.80	1.20	1.80		1.40	1.80	2.90	
E 1	Madrid	0.66	1.38	2.40	4.48	1.60		4.72	11.76
E 2	El Pardo	0.59	1.12	1.28	2.24	1.20		3.04	
E 3	Lagoas	1.00	1.84	3.33	5.84	4.58		5.52	10.72
E 4	Baracaldo	1.20	2.48	4.04	7.04	2.60		4.28	13.36
S1	Stockholm Vanadis	0.64	1.26	2.50	4.00	1.50	3.36	5.30	8.80

Code	Testing Site	flat specimens				helix specimens			
		1 year	**2 years**	**4 years**	**8 years**	**1 year**	**2 years**	**4 years**	**8 years**
S 2	Kattesand	1.50	2.58	5.50	9.60	2.85	4.58	10.00	20.80
S 3	Kvarnvik	1.80	3.02	7.20	16.80	3.50	5.38	12.90	26.40
UK 1	Stratford	1.67	3.97	7.66		1.54	2.31	3.61	
UK 2	Crowthorne	1.10	2.22	4.89		1.19	1.78	3.35	
UK 3	Rye	2.54	4.08	6.18		2.02	2.29	3.47	
UK 4	Fleet Hall	1.34	2.19	4.24		2.27	5.31	7.73	
US 1	Kure Beach	2.01	3.90	6.52	9.60	3.55	6.48	9.72	16.24
US 2	Newark	1.96	3.72			2.15			17.28
US 3	Panama	17.50	37.20		123.90	7.58			226.40
US 4	Res. Tri. Park	0.84							226.40
US 5	Point Reyes	1.73	3.90		3.84	3.51	5.36		10.56
US 6	Los Angeles	1.09	2.38		5.84	1.76			
SU 1	Murmansk	1.10	2.08	3.90		2.10	3.62	7.40	
SU 2	Batumi	1.60	2.74	4.52		2.00	3.68	1.28	
SU 3	Vladivostok	2.30	2.30	4.12		3.10	4.48	6.80	
SU 4	Oymyakon	0.36	0.64	0.68		0.57	0.64	1.04	

Source: D. Knotkova, K. Kreislova, S.W. Dean, Jr., eds., *ISOCORRAG International Atmospheric Exposure Program: Summary of Results* (West Conshohocken, PA, USA: ASTM International, 2010), p. 35.

CORROSION LOSSES OF COPPER (μM) 1, 2, 4, AND 8 YEARS OF EXPOSURE

Code	Testing Site	flat specimens				helix specimens			
		1 year	2 years	4 years	8 years	1 year	2 years	4 years	8 years
ARG 1	Iugazu	0.76	1.82	3.76		0.57	0.86	1.32	
ARG 2	Camet	2.24	3.30	2.60		2.49	2.88	4.68	
ARG 3	Buenos Aires	0.68	1.06	1.88		0.77	1.30	2.12	
ARG 4	San Juan	0.18	0.30	0.80		0.39			
ARG 5	Jubay-Antarct.	2.02	2.34			3.03	4.16		
CND 1	Boucherville	1.10	1.62	2.68	4.16	1.30	1.80	3.44	5.92
CS 1	Kasperské Hory	2.00	3.02	4.18	5.36	2.60	3.80	6.01	7.52
CS 2	Praha-Bèchovice	1.30	2.80	4.58	6.08	1.90	4.20	6.70	8.88
CS 3	Kopisty	3.30	6.28	9.75	12.88	4.20	8.28	13.70	13.52
D 1	Bergisch Glad.	0.60	1.40		3.36	0.78	1.72		4.16
SF 1	Helskinki	0.70	1.00	2.00	3.28	1.30	2.00	3.60	5.52
SF 2	Otaniemi	0.80	1.20	2.00	2.96	1.50	2.40	3.60	5.44
SF 3	Ahtari	0.76	1.20	2.00	2.72	1.10	1.80	2.80	4.24
F 1	Saint Denis	1.20	2.10	2.90	5.68	2.15	2.60	3.90	
F 2	Ponteau Mart.	2.70	4.10	5.40	8.72	7.21	6.10	8.00	
F 3	Picherande	1.40	2.30	3.30		1.45	1.60	2.90	
F 4	St. Remy	1.80	2.90	3.70		3.72	3.40	4.60	
F 5	Salins de Gir.	3.20	4.10	7.50	8.24	5.30	9.10		
F 6	Ostende (B)	3.10	4.20	7.10		3.50	10.90		
F 7	Paris	1.40	2.00	5.10	6.88	2.60	4.70	5.80	
F 8	Auby	1.90	3.20	5.70	9.76	2.40	4.90	8.40	12.96
F 9	Biarritz	3.69	5.10	6.92		4.50	5.40	7.76	
JAP 1	Choshi	1.35	1.82	3.04	4.24	2.29	2.82	6.04	
JAP 2	Tokyo	0.66	1.10	2.24	3.92	1.12	1.82	2.96	
JAP 3	Okinawa	2.10	3.00	4.40		4.30	8.80	9.20	
NZ 1	Judgeford	1.35				1.60			
N 1	Oslo	0.60	1.20	1.88		0.90	1.60	2.16	
N 2	Booregaard	1.40	2.80	4.64		2.70	3.80	6.64	
N 3	Birkenes	1.30	2.00	3.40		1.25	1.80	2.88	
N 4	Tannanger	1.90	2.60	3.48		3.20	4.40	5.52	
N 5	Bergen	1.00	1.60	2.80		1.10	1.40	2.72	
N 6	Svanwik	0.80	1.20	1.60		1.00	0.60	0.41	
E 1	Madrid	0.53	1.02	1.64	2.64	0.80		2.16	3.60
E 2	El Pardo	1.10	2.32	3.08	4.48	1.20		3.04	
E 3	Lagoas	1.00	1.70	2.11	2.88	2.92			3.12
E 4	Baracaldo	1.20	2.32	3.44	5.28	1.50		5.92	10.40

Code	Testing Site	flat specimens				helix specimens			
		1 year	2 years	4 years	8 years	1 year	2 years	4 years	8 years
S1	Stockholm Vanadis	0.60	1.06	1.38	3.20	1.10	1.90	2.84	4.00
S 2	Kattesand	1.70	2.60	3.76	5.60	2.30	3.60	4.60	7.20
S 3	Kvarnvik	2.80	3.32	4.28	5.60	4.90	5.42	7.16	8.80
UK 1	Stratford	1.13	1.98	3.88		1.37	2.88	5.24	
UK 2	Crowthorne	1.10	1.89	3.67		1.37	2.88	5.26	
UK 3	Rye	1.86	2.23	3.84		4.20	13.70	27.10	
UK 4	Fleet Hall	0.93	2.80	4.64		1.58	3.40	6.48	
US 1	Kure Beach	2.85	3.70	6.44	10.64	4.58	7.04	6.96	12.88
US 2	Newark	1.39		3.26	6.80	1.94	2.10		10.48
US 3	Panama	5.46	8.04	18.20	35.60	11.60	13.90	25.10	40.56
US 4	Res. Tri. Park	2.43							
US 5	Point Reyes	2.32	3.20	4.88	5.68	4.43	7.02	8.88	10.40
US 6	Los Angeles	1.16	1.62		4.24	2.04	3.04		6.80
SU 1	Murmansk	1.70	2.62	3.76		2.80	3.12	5.16	
SU 2	Batumi	2.00	4.34	6.04		1.90	4.30	6.24	
SU 3	Vladivostok	1.40	2.18	2.68		2.40	2.98	3.96	
SU 4	Oymyakon	0.09	0.11	0.20		0.11	0.12	0.24	

Source: D. Knotkova, K. Kreislova, S.W. Dean, Jr., eds., *ISOCORRAG International Atmospheric Exposure Program: Summary of Results* (West Conshohocken, PA, USA: ASTM International, 2010), p. 37.

CORROSION LOSSES OF ALUMINUM (μM) 1, 2, 4, AND 8 YEARS OF EXPOSURE

Code	Testing Site	flat specimens				helix specimens			
		1 year	2 years	4 years	8 years	1 year	2 years	4 years	8 years
ARG 1	Iugazu	0.06	0.12	0.12		0.37	0.12	0.16	
ARG 2	Camet	0.19	0.26	1.08		0.85	1.08	2.24	
ARG 3	Buenos Aires	0.06	0.04	0.16		0.44	0.16	1.12	
ARG 4	San Juan	0.03	0.04	0.08		0.16	0.08		
ARG 5	Jubay-Antarct.	1.33	2.38			1.43			
CND 1	Boucherville	0.40	0.36	0.72	10.4	0.44	0.72	1.44	2.40
CS 1	Kasperské Hory	0.50	0.61	0.71	1.28	0.33	0.71	0.41	0.80
CS 2	Praha-Bèchovice	0.60	0.81	1.38	1.60	0.50	1.38	0.70	1.36
CS 3	Kopisty	0.70	1.14	2.16	2.72	0.70	2.16	1.43	2.32
D 1	Bergisch Glad.	0.26	0.08			0.60			0.32
SF 1	Helskinki	0.30	0.46	0.76	1.04	0.50	0.76	1.28	1.92
SF 2	Otaniemi	0.14	0.14	0.32	0.48	0.30	0.32	0.52	0.80
SF 3	Ahtari	0.10	0.04	0.16	0.24	0.45	0.16	0.24	
F 1	Saint Denis	1.20	1.00	1.60	3.28	1.97	1.60	1.60	
F 2	Ponteau Mart.	1.00	1.20	1.70	4.16	13.12	1.70	24.30	
F 3	Picherande	0.30	0.13	0.16		0.44	0.16	0.12	
F 4	St. Remy	0.77	1.20	0.72	2.16	1.50	0.72	3.80	
F 5	Salins de Gir.	0.70	1.20	2.40	4.08	2.80	2.40		
F 6	Ostende (B)	1.50	1.90	3.36		3.30	3.36		
F 7	Paris	0.90	1.70	3.32	3.76	1.20	3.32	3.52	
F 8	Auby	1.70	3.44	6.16	11.68	3.75	6.16	11.50	21.44
F 9	Biarritz	1.20	1.46	2.88		2.40	2.88	8.36	
JAP 1	Choshi	0.33	0.32	0.64	0.96	0.67	0.64	1.92	
JAP 2	Tokyo	0.54	0.62	1.64	4.32	0.41	1.64	10.4	
JAP 3	Okinawa	0.26	0.38	0.52		0.98	0.52	2.12	
NZ 1	Judgeford	0.06	0.12			0.57			
N 1	Oslo	0.15	0.40	0.68		0.74	0.68	0.76	
N 2	Booregaard	0.60	1.00	2.90		1.65	2.90	5.00	
N 3	Birkenes	0.10	0.20	0.48		0.18	0.48	0.32	
N 4	Tannanger	0.60	1.20	1.80		1.23	1.80	4.40	
N 5	Bergen	0.10	0.40	0.76		0.30	0.76	0.78	
N 6	Svanwik	0.10	0.20	0.11		0.20	0.11	0.12	
E 1	Madrid	0.07	0.12	0.20	0.16	0.20	0.20	0.28	0.88
E 2	El Pardo	0.05	0.06	0.12	0.40	0.14	0.12	0.24	

Code	Testing Site	flat specimens				helix specimens			
		1 year	2 years	4 years	8 years	1 year	2 years	4 years	8 years
E 3	Lagoas	0.20	0.22	0.41	0.64	0.60	0.41	0.38	1.84
E 4	Baracaldo	0.20	0.22	0.36	0.64	0.35	0.36	0.84	1.60
S 1	Stockholm Vanadis	0.20	0.32	0.44	0.80	0.43	0.44	1.12	1.60
S 2	Kattesand	0.40	0.56	1.04	1.60	0.90	1.04	1.40	4.80
S 3	Kvarnvik	0.60	0.90	1.44	2.40	1.50	1.44	4.72	9.60
UK 1	Stratford	0.40	0.64	0.97		0.18	0.97	0.56	
UK 2	Crowthorne	0.28	0.51	0.99		0.20	0.99	0.20	
UK 3	Rye	0.37	0.64	1.42		0.52	1.42	0.60	
UK 4	Fleet Hall	0.31	0.86	1.72		0.38	1.72	0.52	
US 1	Kure Beach	0.29	0.34	0.65		0.87	0.65	1.66	
US 2	Newark	0.28	0.44			0.59			
US 3	Panama	0.57	1.02	1.64		1.65	1.64	3.04	
US 4	Res. Tri. Park	0.11							
US 5	Point Reyes	0.22	0.28	0.40		1.33	0.40	7.44	
US 6	Los Angeles	0.56	1.02	1.81		1.47	1.81	4.40	
SU 1	Murmansk	0.80	1.74	1.16		1.80	1.16	6.96	
SU 2	Batumi	0.10	0.24	0.32		0.30	0.32	0.44	
SU 3	Vladivostok	0.30	0.40	0.56		0.70	0.56	2.28	
SU 4	Oymyakon	0.07	0.11	0.08		0.05	0.08	0.12	

Source: D. Knotkova, K. Kreislova, S.W. Dean, Jr., eds., *ISOCORRAG International Atmospheric Exposure Program: Summary of Results* (West Conshohocken, PA, USA: ASTM International, 2010), p. 38.

ATMOSPHERIC CORROSIVITY RANKING OF STEEL AND ZINC AT VARIOUS TEST SITES TWO-YEAR EXPOSURE

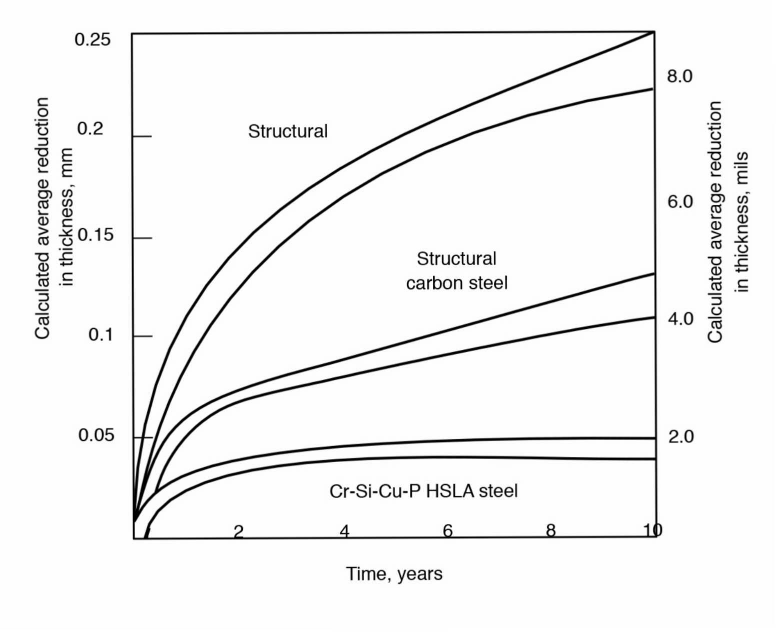
Ranking Steel	Zinc	Location	Weight Loss (g) Steel	Zinc	Loss Ratio Steel/Zinc
1	1	Norman Wells, NWT,Canada	0.73	0.07	10.3
2	2	Phoenix, AR	2.23	0.13	17.0
3	3	Saskatoon, SK, Canada	2.77	0.13	21.0
4	4	Esquimalt, Vancouver Island, BC, Canada	6.50	0.21	31.0
5	15	Detroit, MI	7.03	0.58	12.2
6	5	Fort Amidor Pier, Panama, C.Z.	7.10	0.28	25.2
7	11	Morenci, MI	9.53	0.53	18.0
8	7	Ottawa, ON, Canada	9.60	0.49	19.5
9	13	Potter County, PA	10.00	0.55	18.3
10	31	Waterbury, CT	11.00	1.12	9.8
11	10	State College, PA	11.17	0.51	22.0
12	28	Montreal, PQ, Canada	11.44	1.05	10.9
13	6	Melbourne, Australia	12.70	0.34	37.4
14	20	Halifax (York Redoubt), NS, Canada	12.97	0.70	18.5
15	19	Durham, NH	13.30	0.70	19.0
16	12	Middletown, OH	14.00	0.54	26.0
17	30	Pittsburgh, PA	14.90	1.14	13.1
18	27	Columbus, OH	16.00	0.95	16.8
19	21	South Bend, PA	16.20	0.78	20.8
20	18	Trail, BC,Canada	16.90	0.70	24.2
21	14	Bethlehem, PA	18.3	0.57	32.4
22	33	Cleveland, OH	19.0	1.21	15.7
23	8	Miraflores, Panama, C.Z.	20.9	0.50	41.8
24	29	London (Battersea), England	23.0	1.07	21.6
25	24	Monroeville, PA	23.8	0.84	28.4
26	35	Newark, NJ	24.7	1.63	15.1
27	16	Manila, Philippine Islands	26.2	0.66	39.8

Ranking Steel	Zinc	Location	Weight Loss (g) Steel	Zinc	Loss Ratio Steel/Zinc
28	32	Limon Bay, Panama, C.Z.	30.3	1.17	25.9
29	39	Bayonne, NJ	37.7	2.11	17.9
30	22	East Chicago, IN	41.1	0.79	52.1
31	9	Cape Kennedy, FL (1/2 mile from ocean)	42.0	0.50	84.0
32	23	Brazos River, TX	45.4	0.81	56.0
33	40	Pilsey Island, England	50.0	2.50	20.0
34	42	London (Stratford), England	54.3	3.06	17.8
35	43	Halifax (Federal Building), NS, Canada	55.3	3.27	17.0
36	38	Cape Kennedy, FL (60 yards from ocean, 60-ft. elevation)	64.0	1.94	33.0
37	26	Kure Beach, NC (800-ft. lot)	71.0	0.89	80.0
38	36	Cape Kennedy, FL (60 yards from ocean, 30-ft. elevation)	80.2	1.77	45.5
39	25	Daytona Beach, FL	144.0	0.88	164.0
40	44	Widness, England	174.0	4.48	39.0
41	37	Cape Kennedy, FL (60 yards from ocean, ground level)	215.0	1.83	117.0
42	34	Dungeness, England	238.0	1.60	148.0
43	17	Point Reyes, CA	244.0	0.67	364.0
44	41	Kure Beach, NC (80-ft. lot)	260.0	2.80	93.0
45	45	Galeta Point Beach, Panama, CZ	336.0	6.80	49.4

[a]Specimen size 150 × 100 mm (6 × 4 in.)

Source: W.W. Kirk, H.H. Lawson, eds., ASTM STP1239, *Atmospheric Corrosion* (West Conshohocken, PA, USA: ASTM International, 1990). Reprinted with permission, copyright ASTM.

ATMOSPHERIC CORROSION OF STEEL VS. TIME IN AN INDUSTRIAL ATMOSPHERE



Source: L.J. Korb, *Metals Handbook*, 9th ed., vol. 13 (Materials Park, OH, USA: ASM International, 1987), p. 1304. Reprinted with permission from ASM International.

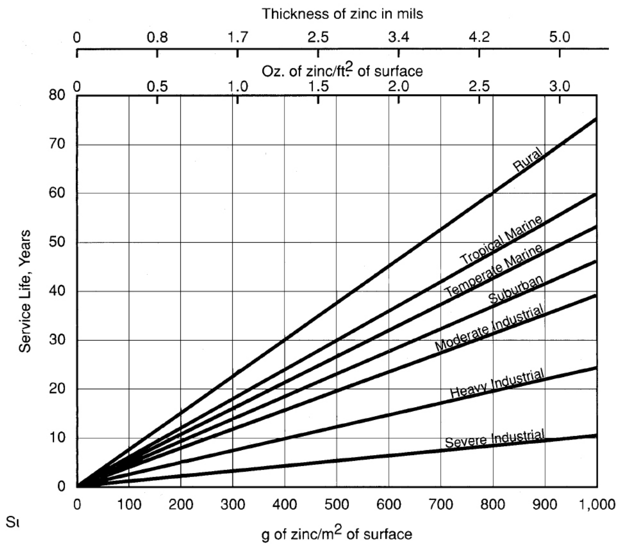
CORROSION OF STRUCTURAL STEEL IN VARIOUS ENVIRONMENTS

Type of Atmosphere	Time, Yr.	Average Reduction in Thickness, Mils[a]					
		Structural Carbon Steel	Structural Copper Steel	UNS K11510[b]	UNS K11430[c]	UNS K11630[d]	UNS K11576[e]
Industrial (Netwark, NJ)	3.5	3.3	2.6	1.3	1.8	1.4	2.2
	7.5	4.1	3.2	1.5	2.1	1.7	–
	15.5	5.3	4.0	1.8	–	2.1	–
Semi-industrial (Monroeville, PA)	1.5	2.2	1.7	1.1	1.4	1.2	1.6
	3.5	3.7	2.5	1.2	2.1	1.4	2.4
	7.5	5.1	3.2	1.4	2.4	1.7	–
	15.5	7.3	4.7	1.8	–	1.8	–
Semi-industrial (South Bend, PA)	1.5	1.8	1.4	1.0	1.3	1.0	1.5
	3.5	2.9	2.2	1.3	1.9	1.5	2.4
	7.5	4.6	3.2	1.8	2.7	1.9	–
	15.5	7.0	4.8	2.2	–	2.5	–
Rural (Potter County, PA)	2.5	–	1.3	0.8	1.2	–	–
	3.5	2.0	1.7	1.1	1.4	1.2	1.8
	7.5	3.0	2.5	1.3	1.5	1.5	–
	15.5	4.7	3.8	1.4	–	2.0	–
Moderate marine	0.5	0.9	0.8	0.6	0.8	0.7	1.0
(Kure Beach, NC, 800 ft. from ocean)	1.5	2.3	1.9	1.1	1.7	1.2	1.7
	3.5	4.9	3.3	1.8	2.5	1.9	2.2
	7.5	5.6	4.5	2.5	3.7	2.9	–
Severe marine	0.5	7.2	4.3	2.2	3.8	1.1	0.7
(Kure Beach, NC, 80 ft. from ocean)	2.0	36.0	19.0	3.3	12.2	–	2.1
	3.5	57.0	38.0	–	28.7	3.9	3.9
	5.0	f	f	19.4	38.8	5.0	–

a) To obtain equivalent values in µm, multiply listed value by 25. b) ASTM A242 (type 1). c) ASTM A588 (grade A). d) ASTM A514 (type B) and A517 (grade B). e) ASTM A514 (type F) and A517 (grade F). f) Specimen corroded completely away.

Source: L.J. Korb, *Metals Handbook*, 9th ed., vol. 13 (Materials Park, OH, USA: ASM International, 1987), p.723. Reprinted with permission from ASM International.

EFFECT OF AMOUNT OF ZINC ON SERVICE LIFE OF GALVANIZED SHEET IN VARIOUS ENVIRONMENTS



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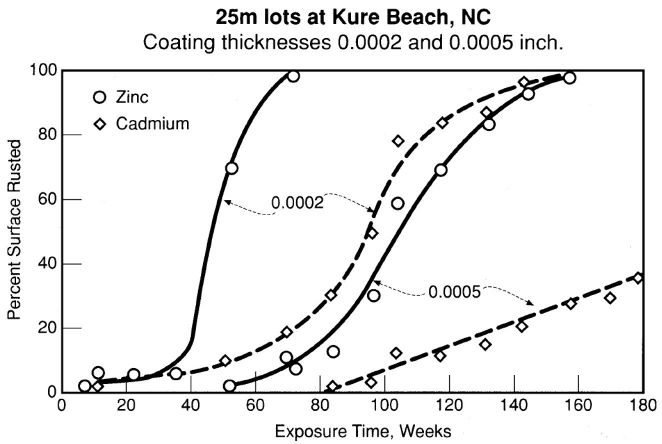
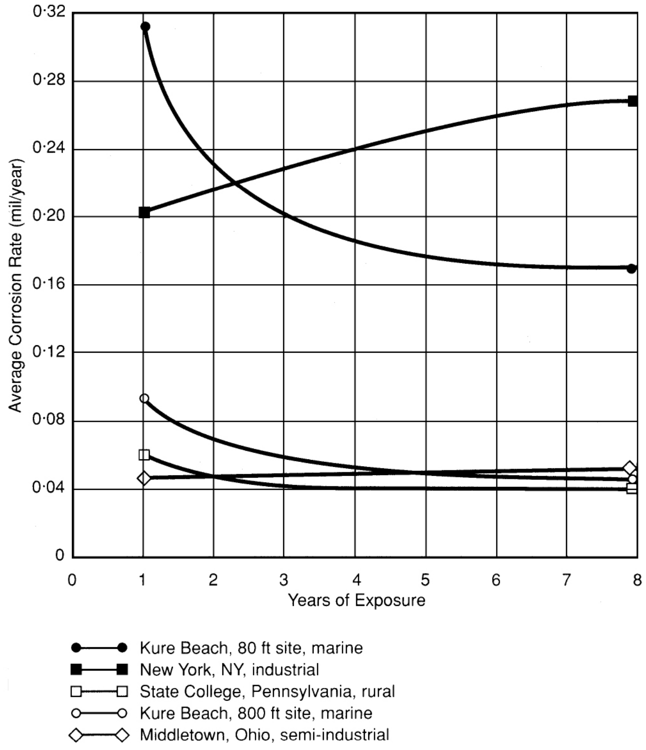
DEVELOPMENT OF RUST ON ZINC AND CADMIUM-PLATED STEELS IN A MARINE ATMOSPHERE



Source: F.W. Fink, et al., "Corrosion of Metals in Marine Environments," Battelle Memorial Institute DMIC Report 254, NTIS AD-712 5B5-S, 1970, pp. 7, 13. Reprinted with permission from Battelle Memorial Institute.

ATMOSPHERIC CORROSION OF ZINC IN VARIOUS LOCATIONS AS A FUNCTION OF TIME



Source: C.J. Slunder, W.K. Boyd, *Zinc, Its Corrosion Resistance*, 2nd ed., International Lead Zinc Research Organization, 1983, p. 42. Reprinted with permission from the International Lead Zinc Research Organization.

LIFETIMES OF HOT DIP ZINC AND ZINC-ALLOY COATINGS

	Years to First Rust			
Environment	**Zn**	**Zn-4Al**	**Zn-7Al**	**Zn-55Al**
Severe marine 25 m from ocean, Kure Beach, NC	4	9	9	15
Moderate marine 250 m from ocean, Kure Beach, NC	16	15	14	>25
Rural Saylorsburg, PA	14	14	14	>25
Industrial Bethlehem, PA	10	10	9	>25

Source: H. Townsend.

ATMOSPHERIC CORROSION OF VARIOUS METALS AND ALLOYS

10-Year Exposure Times Corrosion Rates are Given in mits/yr. (1 mil/yr. = 0.025 mm/yr.).

	New York, NY (urban-industrial)	**La Jolla, CA (marine)**	**State College, PA, (rural)**
Aluminum	0.032	0.028	0.001
Copper	0.047	0.052	0.023
Lead	0.017	0.016	0.019
Tin	0.047	0.091	0.018
Nickel	0.128	0.004	0.006
Ni-Cu Alloy 400	0.053	0.007	0.005
Zinc (99.9%)	0.202	0.063	0.034
Zinc (99.0%)	0.193	0.069	0.042
0.2% C Steel (a) (0.02% P, 0.05% S, 0.05% Cu, 0.02% Ni, 0.02% Cr)	0.48	-	-
Low-alloy steel (a) (0.1% C, 0.2% P, 0.04% S, 0.03%	0.09	-	-

Source: L.J. Korb, *Metals Handbook*, 9th ed., vol. 13 (Materials Park, OH, USA: ASM International, 1987), p. 82. Reprinted with permission from ASM International.

CORROSION OF COPPER ALLOYS IN MARINE ATMOSPHERES

7-Year Exposure of Specimens at 25 Meter Lot at Kure Beach, NC (KB) or Point Reyes, CA (PR). Corrosion Rates by Weight Loss.

UNS	Common Name	Mils/Year KB	Mils/Year PR	Appearance (KB)
C11000	ETP Copper	0.065	0.025	Brown film, smooth, slight patina near edges
C23000	Red Brass	0.033	0.026	Brown-maroon film, smooth
C26000	Cartridge Brass	0.030	0.017	Brown-maroon film, smooth, very slight patina
C42000	Tin Brass	0.024	–	Dark maroon, smooth
C50500	Phos. Bronze E (1.25% Sn)	0.069	0.017	"Mink brown," slight patina
C51000	Phos. Bronze. A (5% Sn)	0.099	–	Maroon film, heavy etch
–	Alum. Bronze (7.5% Al)	0.013	–	Light tan film, smooth
C70400	Copper-Nickel (5% Ni)	0.033	–	Dark brown, plus patina streaks on panel face
C70700	Copper-Nickel (10% Ni)	0.038	–	Uniform maroon with patina at edges
C71100	Copper-Nickel (22% Ni)	0.031	–	Greenish brown, green near edges, slight etch
C74500	Nickel Silver (10% Ni)	0.024	0.010	Brown with slight patina film in center, green near edges, smooth
C75200	Nickel Silver (18% Ni)	0.021	–	Brown film in center, green near edges, smooth

Source: F.W. Fink, et al., "Corrosion of Metals in Marine Environments," Battelle Memorial Institute DMIC Report 254, NTIS AD-712 5B5-S, 1970, pp. 7, 13. Reprinted with permission from Battelle Memorial Institute.

CORROSION OF COPPER AND COPPER ALLOYS IN µm/Year

Material	New York/Newark	State College, PA	Kure Beach, La Jolla
T.P. copper	1.42	0.58	1.45
Phosphor bronze	1.91	0.56	2.51
Red brass	1.80	0.51	0.58
Yellow brass	2.16	0.58	0.46
90-10 Cu Ni	3.78	2.08	2.90
Tin brass	1.73	0.76	0.61
Admiralty metal	2.51	0.51	0.33
Manganese bronze	8.64	0.48	2.02
Si Al bronze	1.27	0.33	0.33
10% Ni Silver	1.96	0.64	0.58
18% Ni Silver	2.01	0.61	0.53
Advance	1.55	0.25	0.46
Be copper	1.75	0.76	1.02
12 different coppers	0.81	0.46	1.35

Source: P. Roberge, *Corrosion Basics*, 2nd ed. (Houston, TX, USA: NACE International, 2006), p. 115.

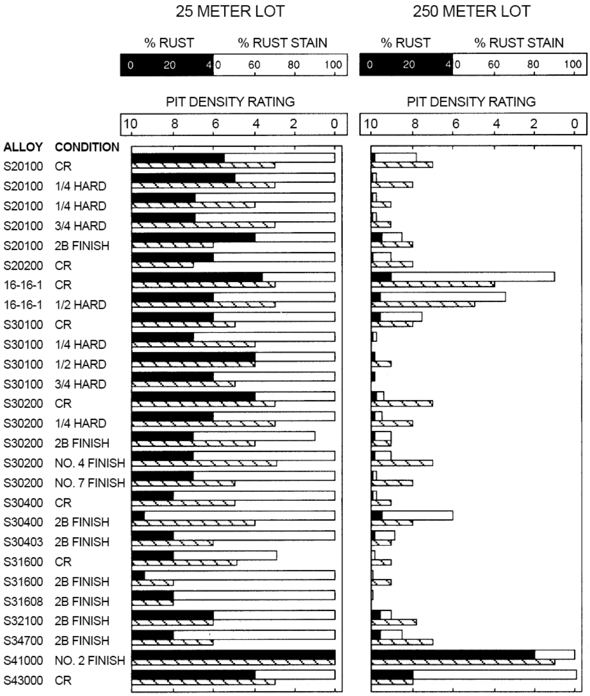
CORROSION IN µm/YEAR OF NICKEL AND ITS ALLOYS IN VARIOUS ATMOSPHERES

Material	New York/Newark	State College, PA	Kure Beach, La Jolla
Nickel	0.15	3.66	0.22
	0.24	1.65	0.23
Monel	0.16	1.57	0.17
	3.56	0.81	0.21
Incoloy	0.06	0.02	0.02
Inconel	0.05	0.03	0.02
Nionel	0.03	0.02	0.02

Source: P. Roberge, *Corrosion Basics*, 2nd ed. (Houston, TX, USA: NACE International, 2006), p. 116.

RELATIVE PERFORMANCE OF STAINLESS STEELS EXPOSED IN A MARINE ATMOSPHERE

KURE BEACH – 26 YEARS



PIT DENSITY RATING

10 + No pits
9 = 0 to 0.1% coverage
8 = 0.1 to 0.25% coverage
7 = 0.25 to 0.5% coverage
6 = 0.5 to 1.0% coverage
5 = 1.0 to 2.5% coverage
4 = 2.5 to 5.0% coverage
3 = 5.0 to 10.0% coverage
2 = 10.0 to 25.0% coverage
1 = 25.0 to 50.0% coverage
0 = > 50% coverage

Source: E.A. Baker, T.S. Lee, ASTM Special Publication 965, "Long-Term Atmospheric Corrosion Behavior of Various Grades of Stainless Steel" (West Conshohocken, PA, USA: ASTM International, 1986), p. 62. Reprinted with permission, copyright ASTM.