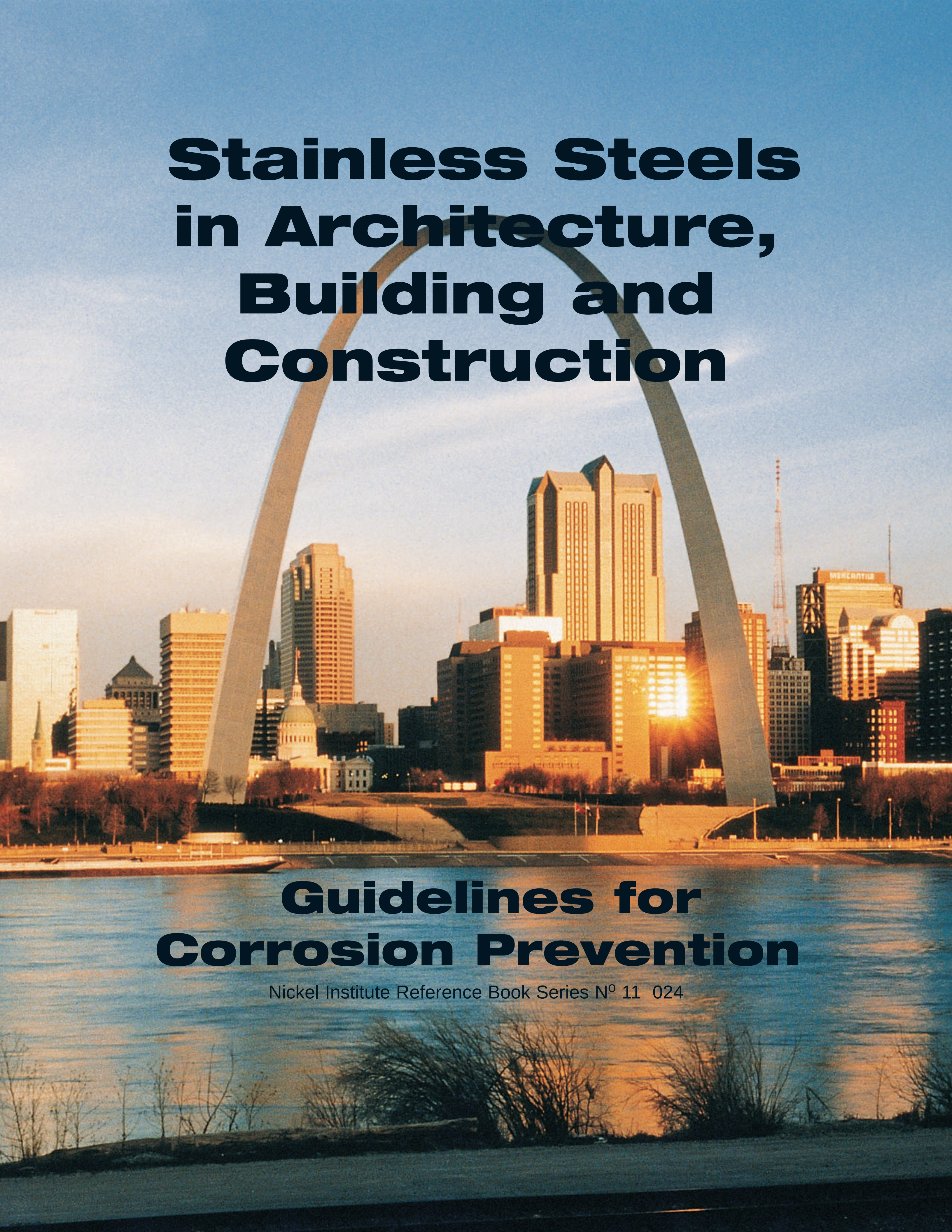


Stainless Steels in Architecture, Building and Construction

Guidelines for Corrosion Prevention

Nickel Institute Reference Book Series № 11 024

Nickel INSTITUTE

knowledge for a brighter future

Stainless Steels in Architecture, Building and Construction

This report was prepared by Catherine Houska, Technical Marketing Resources Inc., Pittsburgh, PA, USA, consultant to the Nickel Institute.

Front Cover: The Gateway Arch (completed in 1965) in St. Louis, Missouri, is the second largest structural application for stainless in the world (904 metric tons) and is exposed to moderate pollution levels. The exterior Type 304 plate has a No. 3 polished finish and is cleaned only by natural rain washing. (Courtesy United States National Park Service)

TABLE OF CONTENTS

INTRODUCTION

Stainless steel is one of the most durable materials used in architecture, building, and construction. With appropriate grade and finish selection, design, fabrication, and maintenance, the appearance and properties of the stainless steel will remain unchanged over the life of the building. These properties make stainless steel a popular choice for buildings designed to last 100 or more years, aggressive environments, applications where security is a concern, and high traffic areas.

Stainless steels are corrosion-resistant because they form a thin, protective passive film on their surface. This film forms spontaneously when chromium in the stainless steel reacts with oxygen in the air. If the film is damaged or removed during fabrication or polishing, it self-repairs quickly as long as the stainless steel surface is clean. Because stainless steels do not suffer general corrosion and become thinner, the term “corrosion allowance” has no meaning in stainless steel structural design.

Atmospheric corrosion, tarnishing, pitting, crevice corrosion, embedded iron, erosion/corrosion, galvanic corrosion, and stress corrosion cracking can impact the performance and appearance of building materials. This brochure discusses these issues and stainless steel’s performance relative to other construction materials.

DESIGN, FABRICATION, MAINTENANCE AND SURFACE FINISH

PRACTICAL GUIDELINES FOR DESIGN AND FABRICATION

This section provides an overview of general design considerations. Examples of designs that can cause corrosion and alternate designs that help prevent corrosion are illustrated. Qualified, experienced stainless steel fabricators and contractors will be familiar with these guidelines, but it is important for the designer to know them as well. When designing and fabricating in stainless steel:

- Evaluate the environment and probable cleaning regime to determine the likelihood of accumulated deposits and air pollutants such as soot, iron oxide particles, sulphur dioxide, and salt exposure before selecting the stainless steel grade.
- Use a design that allows rain to rinse away surface deposits.
- Specify a higher grade of stainless steel in sheltered areas that are not washed regularly.
- Seal crevices in areas exposed to moisture and/or aggressive corrodants.
- Use a stainless steel fastener with equivalent or higher corrosion resistance than the component being fastened.
- Never use carbon steel brushes or steel wool on stainless steel. Use stainless steel brushes or soft-bristle brushes made of an inert material.
- Never use hydrochloric or muriatic acid on or around stainless steels. If muriatic acid is accidentally splashed on stainless, it should be washed immediately with large quantities of water before the acid severely damages the stainless steel.
- Dissimilar metals should be electrically isolated from each other in applications where they may get wet. This can be achieved using inert washers, protective coatings like paint, and other physical barriers that prevent direct contact. Dissimilar metals should be avoided in applications where standing water is likely and it is not possible to insulate the metals.
- If the design requires welding sections heavier than about 0.125 inches (3 mm) and the weld area will be exposed to a corrosive environment, use low carbon versions of the stainless steels (e.g., 304L or 316L) to reduce the risk of sensitization and improve weld corrosion resistance.
- If a filler metal is used in welding, its corrosion resistance should be equivalent to or greater than the corrosion resistance of the base metal.
- Weld imperfections, such as blowholes, cracks, slag or weld spatter, are potential sites for corrosion and should be repaired or removed.
- Visible welds should be ground smooth and polished to match the parent metal surface finish, taking care to remove any traces of spatter and heat tint.
- Do not use abrasive polishing or blasting materials that have been used previously on carbon steel. This will embed carbon steel in the surface.
- Clean tools and work areas previously used for carbon steel to remove iron particles and prevent their transfer to the stainless steel surface.
- Protect the stainless steel during fabrication, shipping, and installation with paper or strippable plastic film.
- Clean grease, oil, lubricants, paint, and crayon markings from the surface prior to welding to prevent weld contamination. Surface chromium depletion and a subsequent reduction of corrosion resistance may be caused by inadequate gas shielding during welding or insufficient heat tint removal.

Stainless steel is specified for its corrosion resistance and long service life. Even with appropriate grade selection, corrosion problems can occur in crevices and areas where water collects. The design rules for other architectural metals are also important for stainless steel. Examples of design details that can lead to corrosion problems and alternatives that minimize the potential for corrosion are shown in *Figure 1*.[1, 21]

Table 1 International cross-reference to mill and polished finishes

Finish Type	USA (ASTM A 480)	Japan (JSSA)	European Standard EN 10088
Mill	2D	2D	2D
	2B	2B	2B
	Bright annealed (BA)	BA	2R
Polished	No. 3	No. 3	1G or 2G
	No. 4	No. 4	1J or 2J
	–	No. 240	1K or 2K
	No. 7	No. 7	1P or 2P
	No. 8		1P or 2P

Note: In the European Standard, 1 indicates a hot rolled product and 2 a cold rolled product.

SURFACE FINISH

Surface roughness is an important factor in corrosion performance in exterior applications. *Table 1* provides an international cross-reference to common finishes and *Table 2* and *Figure 2* show the range of surface roughnesses associated with those finishes in North America. Typical surface roughness ranges vary with the supplier. Polished finishes produced specifically for architecture are usually smoother, and lighter gauge sheet and strip generally have smoother finishes than heavier gauges.

Research has shown a direct correlation between surface finish roughness and the likelihood of corrosion.[2] Smoother surface finishes typically retain less dirt and debris, and provide better corrosion performance than rougher finishes. For that reason, European Standard EN 10088 recommends a surface roughness of R_a 20 micro-inches or 0.5 microns or less for polished finishes used in environments with high levels of particulate, corrosive pollution, and/or salt exposure and in applications where regular maintenance is unlikely. Similar guidelines should be followed for finishes produced by means other than polishing.

For most coined or embossed finishes, the roughness of the finish should be measured prior to pressing the pattern into the metal. There are two exceptions. If the coined or embossed finish simulates another finish such as abrasive blasting or polishing, or if the pattern is likely to retain dirt and debris, the roughness of the final finish should be measured.

Dirt accumulations are greater on horizontal or semi-horizontal surfaces and in sheltered locations. If the location tends to collect dirt and/or a rougher surface finish is selected, it may be necessary to use a more corrosion-resistant stainless steel to achieve the desired long-term corrosion performance.

Electropolishing is sometimes used to make components with a No. 3 or No. 4 polish brighter and more reflective. It also smoothes the surface, typically reducing the original surface roughness by about half, which can improve corrosion performance.

Some finishes have obvious directionality. These include the rougher polished (No. 3 and No. 4) and embossed finishes. The surface will collect less dirt and rain washing will be more effective if the finish grain orientation is vertical rather than horizontal.

MAINTENANCE

Stainless steel looks best and provides maximum corrosion resistance when it is cleaned regularly. Corrosion may occur if dirt, grime and surface stains containing corrosive substances are left on the stainless steel surface. Routine cleaning preserves stainless steel's appearance. The frequency of cleaning will depend on aesthetic requirements, severity of the environment, suitability of the stainless steel grade and finish for that environment, the presence or lack of heavy rains to clean the surface, and the design.

Figure 1 Unsuitable metal design details for locations with potential corrosion problems and typical solutions[1, 21]

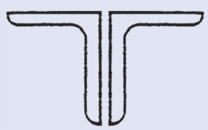
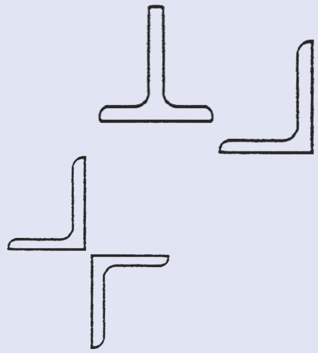
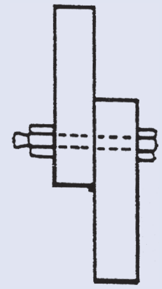
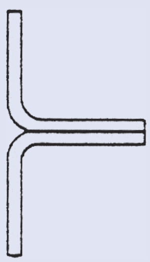
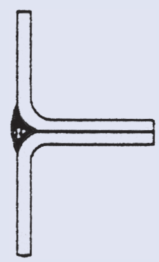
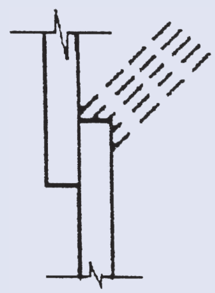
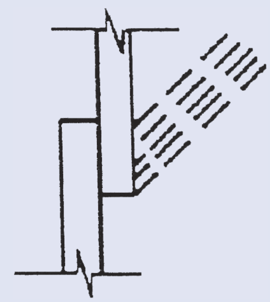
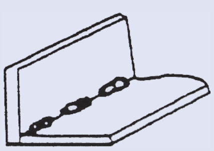
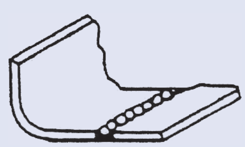
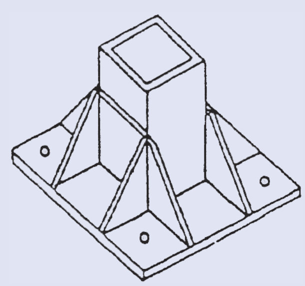
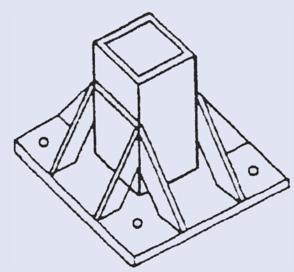
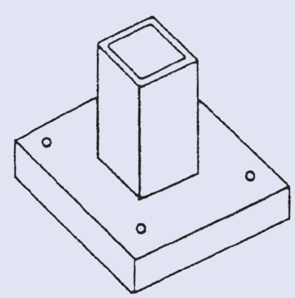
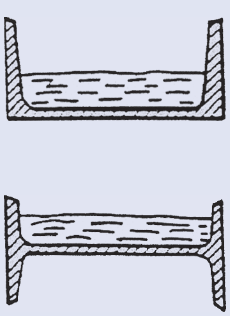
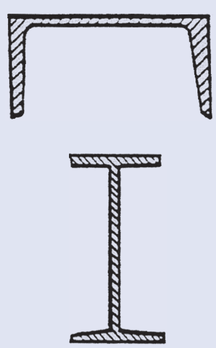
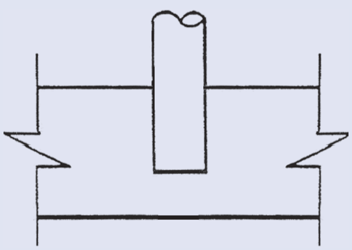
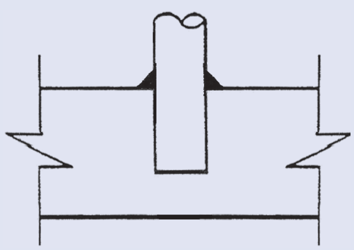
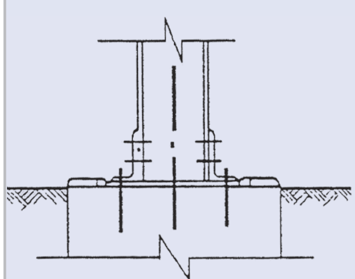
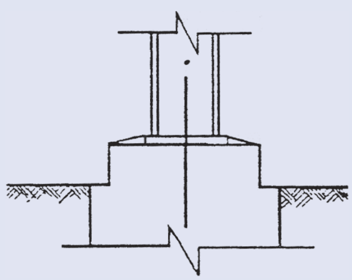
Problem	Typical Solution	Problem	Typical Solution
Backs of double angle create a crevice where dirt and moisture can accumulate 	**Design as single angle truss, or use T-section** 	**Dirt accumulates and moisture penetrates into crevices created by bolted joints** 	**Consider using welded or butt-welded joints or sealing with mastic** 
Potential corrosion due to angles creating a crevice 	**Close crevice by sealing or welding** 	**Lapped joint creates ledge exposed to weather** 	**Arrange joint so that ledge is not on the weather side** 
Sharp corners and discontinuous welding 	**Round corners and continuous welding** 	**Gussets create pockets for dirt and moisture** 	**Design without gussets or allow drainage**  
Channels or I-beams could collect dirt and moisture 	**Invert section or design to avoid retention of moisture and dirt** 		

Figure 1 (cont'd) ***Unsuitable metal design details for locations with potential corrosion problems and typical solutions[1, 21]***

Problem	Typical Solution
Possible crevice corrosion where stainless steel enters concrete 	**Avoid crevice corrosion with sealant** 
Base and bolts at ground level result in water retention and corrosion 	**Column baseplate above ground level. Holding-down bolts not exposed to corrosion. Stalk of column well clear of ground level. Slope for drainage.** 

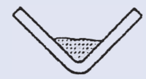
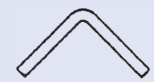
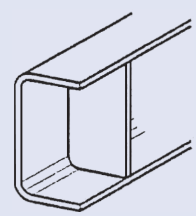
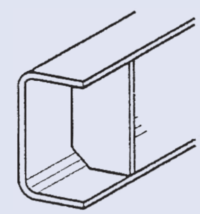
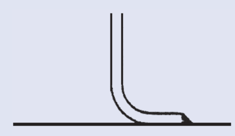
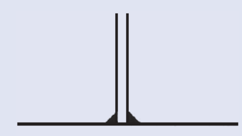
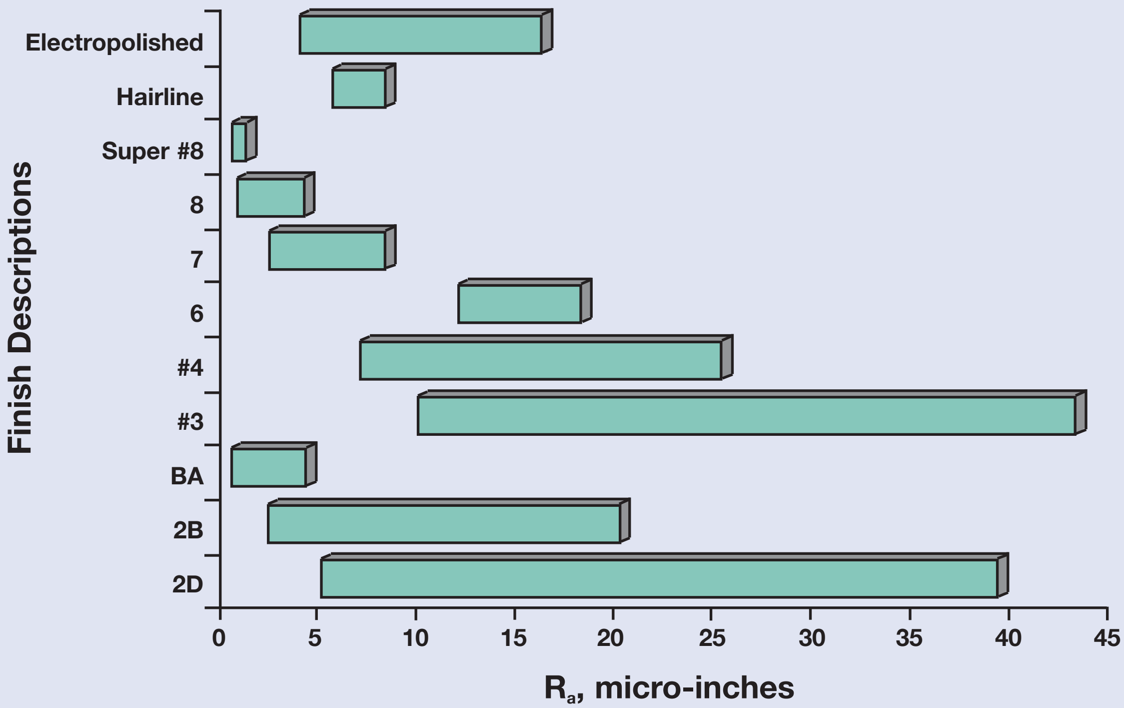
Problem	Typical Solution
Angle collects dirt and moisture 	**Invert angle** 
Welding only the bottom of the joint creates a crevice 	**Weld the top of the joint** 
Reinforcement prevents drainage 	**Leave gap to allow drainage** 
A crevice is created by welding a curved member at one end 	**Use a straight member and weld both sides** 

Table 2 ***Typical surface roughness ranges for cold rolled sheet and strip from North American stainless steel suppliers***

ASTM A 480 Finish Descriptions	R_a and RMS Surface Roughness Equivalents			
	R_a, micro-inches	R_a, microns	RMS, micro-inches	RMS, microns
2D	5.0–39.0	0.13–1.0	6.4–49.2	0.16–1.25
2B	2.4–20.0	0.06–0.51	3.0–25.1	0.08–0.64
BA	0.5–4.0	0.01–0.10	0.49–4.9	0.01–0.13
#3	10.0–43.0	0.25–1.10	12.3–54.1	0.31–1.37
#4	7.0–25.0	0.18–0.64	8.9–31.5	0.23–0.80
6	12.0–18.0	0.30–0.46	14.8–22.6	0.37–0.57
7	2.4–8.0	0.06–0.20	3.0–9.8	0.07–0.25
8	0.74–4.0	0.019–0.10	0.9–4.9	0.02–0.13
Super No. 8	0.4–0.8	0.01–0.02	0.5–1.0	0.01–0.03
Hairline	5.5–8.0	0.14–0.20	6.9–9.8	0.18–0.25
Electropolished	4.0–16.0	0.10–0.41	4.9–20.2	0.13–0.50

Note: Data for sheet and strip were obtained from North American suppliers. The highest and lowest values were used to create the surface roughness range and include both light and heavy gauges. Lighter gauges generally have smoother finishes than heavier gauges and would be at the bottom end of the range. Surface roughness will vary across sheet width and length.

Figure 2 Typical surface roughness ranges for cold rolled sheet and strip from North American stainless steel suppliers

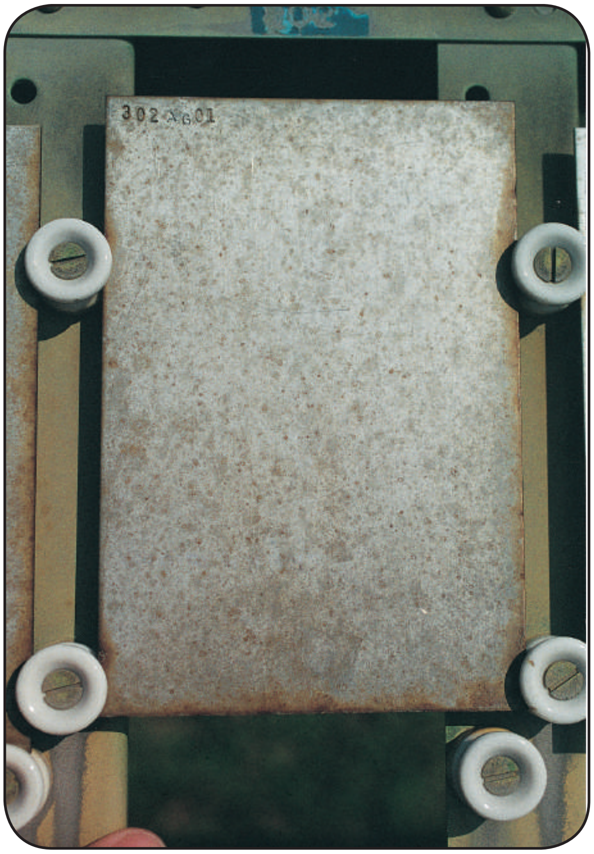


When possible, designs should take advantage of natural rain washing and include building washing systems. Designing for rain cleaning and stainless steel grade and finish selection are particularly important in structures that will never or rarely be cleaned, like industrial buildings and monumental structures such as the Gateway Arch.

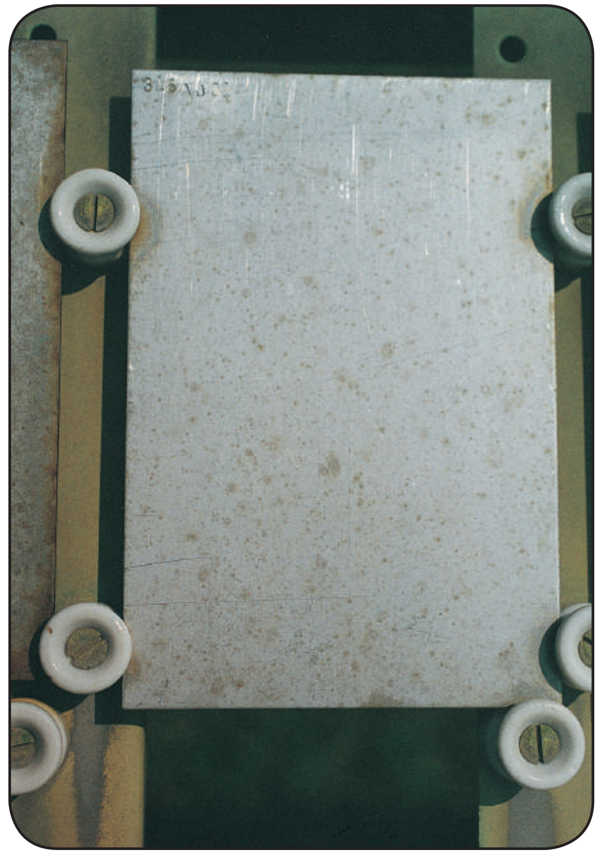
Stainless steel is easy to clean and regular cleaning with appropriate products will not change the appearance of the finish over time. Loose dirt is rinsed off with clean water. A mild detergent or 5% ammonia and water solution is applied with a soft clean cloth. This is rinsed off with clean water and then wiped or squeegeed dry. A soft-bristle brush can be used to loosen dirt and a degreaser to remove oil stains. Cleaning products should not contain chlorides or harsh abrasives.

If the surface has been neglected or there are stubborn deposits, a mild, non-acidic, non-scratching, abrasive powder that does not contain chlorides can be used on bare stainless steel. More aggressive cleaning can damage the finish and the supplier should be consulted before proceeding. It is best to test cleaning products on a stainless steel sample or inconspicuous location before use. Although buildings can often be restored to their original appearance after many years of neglect, remedial cleaning is more costly and can have uncertain results. Cleaning guidelines can be found in the NI publication 11 014, *Guidelines for Maintenance and Cleaning*.

Courtesy Technical Marketing Resources, Inc.

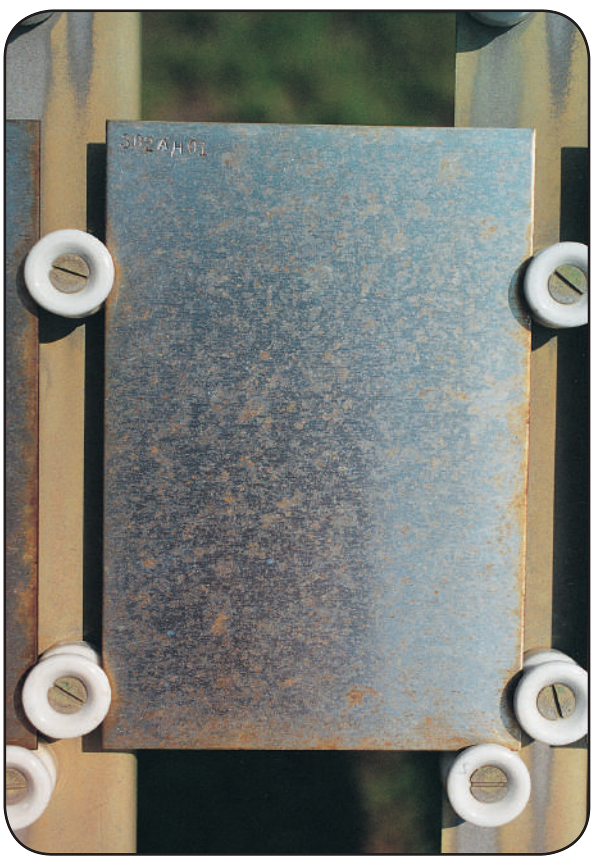


Type 302, 2B finish.

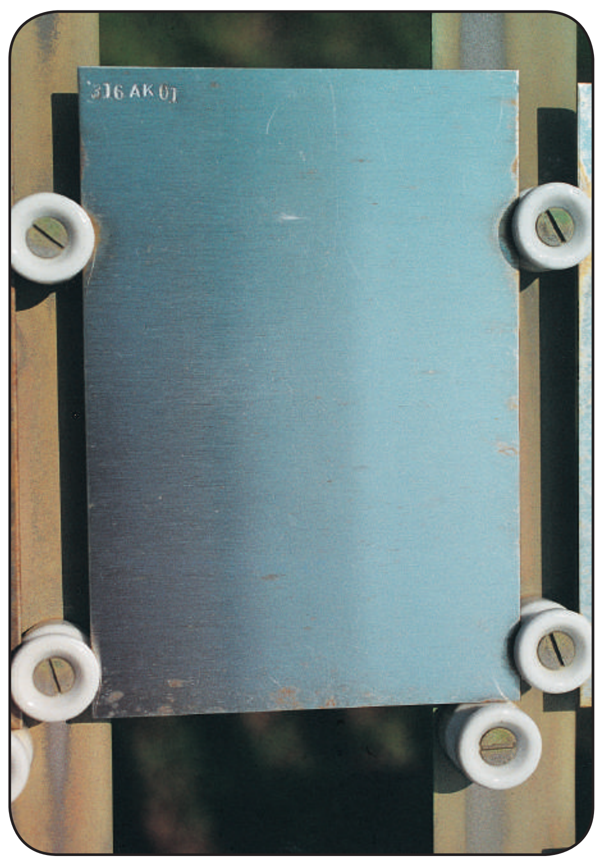


Type 316, 2B finish.

Courtesy Technical Marketing Resources, Inc.



Type 302, No. 4 polish.



Type 316, No. 4 polish.

These Type 316 and 302 samples were exposed 800 feet (250 metres) from the ocean for forty years at Kure Beach, North Carolina with only natural rain cleaning.

ATMOSPHERIC CORROSION

ATMOSPHERIC EXPOSURE TESTING

Potentially corrosive atmospheric pollutants, wind-borne marine salt, temperature, humidity, rainfall, and deicing salt exposure must be taken into consideration when selecting an appropriate stainless steel. Localized pollution and the direction of the prevailing winds can cause differences in the corrosiveness of sites that are only a few miles or kilometres apart.

Courtesy Specialty Steel Industry of North America

Above – The Inland Steel Building (completed in 1957) is on a busy street in downtown Chicago and has Type 302 exterior wall panels with a No. 4 polish. They are exposed to deicing salt and pollution. The panels have always been cleaned three to four times per year when the windows are washed. It is in excellent condition.

For testing and material selection, service environments are classified as rural, urban, industrial, and marine. These categories refer to the general environment and not to localized conditions such as the immediate proximity of a source of strong pollution like a smokestack. Possible environmental changes during the building life should be evaluated. For example, will a rural site become urban or industrial?

Within each category, levels of severity have been established. To classify the severity of an environment, rainfall, air temperature, pollution and other factors have been monitored. Because no two environments are exactly alike, the data should be used as a general performance guideline for localities with similar pollution levels and climate in conjunction with the guidelines in *Table 3*.

Carbon steel calibrating samples are used to compare the severity of atmospheric corrosion test sites around the world.[3,4] See *Table 4*. Comparative metal corrosion data from many of these sites is provided in this brochure. This data can be used in conjunction with *Table 4* and a thorough evaluation of the site to predict probable metal performance in locations with similar environments and carbon steel corrosion rates. Although some of these sites are in locations where deicing salts are used, the calibrating samples were not exposed to salt. Salt exposure makes an environment much more aggressive. The likelihood of deicing salt exposure should be considered when evaluating the severity of sites.

An electrolyte must be present for corrosion to occur. An electrolyte is a water solution that can conduct an electric current because it contains chemicals, such as chlorides. The water could come from rain, condensation of

Table 3 Characteristics of the most and the least corrosive environments

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 and/or condensation • 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 32°F (0°C) • High air temperatures with low humidity

Table 4 Corrosion rates of carbon steel calibrating samples at various test sites

Test Site	Atmosphere	Corrosion rate	
		mils/year	mm/year
Canada			
Norman Wells, Northwest Territories	Polar	0.03	0.001
Esquimalt, Vancouver Island, British Columbia	Rural marine	0.5	0.013
Montreal, Quebec	Urban	0.9	0.023
Trail, British Columbia	Industrial	1.3	0.033
England			
Dungeness	Industrial marine	19.22	0.49
Pilsey Island	Industrial marine	4.04	0.103
London, Battersea	Industrial	1.8	0.046
Panama			
Fort Amidor Pier	Tropical marine	0.57	0.014
Limon Bay	Tropical marine	2.45	0.062
Miraflores	Tropical marine	1.69	0.043
Galeta Point	Tropical marine	27.14	0.69
South Africa			
Durban, Salisbury Island	Marine	2.20	0.056
Durban Bluff	Severe marine	10.22	0.26
Cape Town Docks	Mild marine	1.84	0.047
Walvis Bay military base	Severe marine	4.33	0.11
Simmonstown	Marine	0.63	0.016
United States			
Phoenix, Arizona	Rural arid	0.18	0.005
Point Reyes, California	Marine	19.71	0.50
Waterbury, Connecticut	Industrial	0.89	0.023
Cape Canaveral, Florida	Marine		
0.5 miles (0.8 km) from ocean		3.39	0.086
180 ft (55 m) from ocean			
elevation 60 ft (18 m)		6.48	0.165
elevation 30 ft (9 m)		17.37	0.44
ground level		5.17	0.131
Beach		42.0	1.070
Daytona Beach, Florida	Marine	11.63	0.295
East Chicago, Indiana	Industrial	3.3	0.084
Detroit, Michigan	Industrial	0.57	0.015
Moenci, Michigan	Urban	0.77	0.020
Durham, New Hampshire	Rural	1.1	0.028
Kure Beach, North Carolina	Marine		
800 ft (250 m) from ocean		5.73	0.145
80 ft (25 m) from ocean		21.0	0.53
Newark, New Jersey	Industrial	2.0	0.051
Bayonne, New Jersey	Industrial	3.1	0.079
Cleveland, Ohio	Industrial	1.5	0.038
Columbus, Ohio	Industrial	1.3	0.033
Middletown, Ohio	Semi-industrial	1.1	0.028
Bethlehem, Pennsylvania	Industrial	1.5	0.038
Monroeville, Pennsylvania	Semi-industrial	1.9	0.048
State College, Pennsylvania	Rural	0.9	0.023
Pittsburgh, Pennsylvania	Industrial	1.2	0.030
Potter County, Pennsylvania	Rural	0.8	0.020
Brazos River, Texas	Industrial marine	3.7	0.094

humidity, or fog. The pattern and quantity of rainfall in an area are critical in determining the severity of an environment. Especially wet or especially dry climates tend to be less corrosive but there are exceptions to this rule. If surfaces are regularly damp because there are small amounts of rain at frequent intervals, persistent high humidity, regular fog or another source of moisture and there are corrosive deposits on the surface, a potentially aggressive environment exists. Small amounts of moisture will not wash deposits from the surface and will combine with them to create a corrosive solution.

Heavier rains dilute the electrolyte and provide a washing action to remove potentially harmful deposits. Thus a simple indication of annual rainfall at a particular site is not sufficient to determine the severity of that location.

Air temperature is often reported and can have contradictory effects. Corrosion proceeds more rapidly with increasing temperatures but, if higher temperatures are associated with low humidity, the water will quickly evaporate and the corrosion risk will be reduced.

SELECTING SUITABLE GRADES FOR SPECIFIC LOCATIONS

The most commonly used stainless steels for architectural applications are Types 304 (S30400) and 316 (S31600). The 300-series stainless steels, such as Types 304 and 316, are iron-chromium-nickel alloys. They have an austenitic microstructure, which combines strength with ductility, and are not magnetic. The low carbon grades, Type 304L (S30403) and Type 316L (S31603), improve weld corrosion resistance when section thicknesses are greater than about 0.125 inches (3 mm).
The general corrosion resistance of Type 304 is equivalent to Type 304L, and Type 316 is equivalent to Type 316L.

Type 430 (UNS S43000) is less corrosion-resistant and less frequently used in exterior applications. The 400-series stainless steels, such as Type 430, are iron-chromium alloys, have a ferritic microstructure and are magnetic.

Types 316, 304, and 430 have been tested extensively in rural, urban, industrial, and marine environments. In most applications, one of these stainless steels will meet aesthetic and service life criteria.

Highly alloyed stainless steels are sometimes needed for aggressive environments. Because the corrosion resistance and mechanical properties of these grades span a broad range, a specialist should be consulted for optimal material selection. The following more highly alloyed austenitic grades are listed in order of increasing corrosion resistance: Type 317L (S31703), Type 317LMN (S31726), Alloy 904L (N08904), and the 6% molybdenum stainless steels (i.e., S31254, N08367, N08926). Duplex stainless steels such as 2205 (S32205/S31803) have been used for structural applications and provide corrosion performance that is comparable to 904L and Type 317LMN. This list is not exhaustive and other highly alloyed stainless steels may be selected for specific applications.

Alloying element additions enhance and modify material properties. Molybdenum improves resistance to pitting and crevice corrosion and is particularly helpful in preventing chloride damage. Increasing chromium improves overall corrosion resistance and nickel increases toughness, ductility, weldability, and resistance to reducing acids. *Table 5* shows the chemical composition of these stainless steels.

Table 6 presents grade selection guidelines based on long-term stainless steel exposure data for marine and polluted locations reported by Baker and Lee[5], Chandler[6], Karlssen and Olsson[7], and Evans.[8,9] The location categories refer to general conditions. Localized factors, such as proximity to a flue discharging corrosive gases, must be considered when selecting an appropriate stainless steel.

Table 5 Unified Numbering System (UNS) chemical compositions*

UNS No.	Common or Trade Name	C	Cr	Cu	Mn	Mo	N	Ni	P	S	Si	Fe
S43000	430	0.12	16.0–18.0	–	1.00	–	–	–	0.040	0.030	1.00	rem
S30400	304	0.08	18.0–20.0	–	2.00	–	–	8.0–10.5	0.045	0.030	1.00	rem
S31254	254 SMO	0.020	19.5–20.5	0.50–1.00	1.00	6.0–6.5	0.180–0.220	17.5–18.5	0.030	0.010	0.80	rem
S31600	316	0.08	16.0–18.0	–	2.00	2.00–3.00	–	10.0–14.0	0.045	0.030	1.00	rem
S31703	317L	0.030	18.0–20.0	–	2.00	3.0–4.0	–	11.0–15.0	0.045	0.030	1.00	rem
S31726	317LMN	0.03	17.0–20.0	0.75	2.00	4.0–5.0	0.10–0.20	13.5–17.5	0.045	0.030	0.75	rem
S31803	2205	0.030	21.0–23.0	–	2.00	2.5–3.5	0.08–0.20	4.5–6.5	0.030	0.020	1.00	rem
S32205	2205	0.030	22.0–23.0	–	2.00	3.0–3.5	0.14–0.20	4.5–6.5	0.030	0.020	1.00	rem
N08367	AL-6XN	0.030	20.0–22.0	–	2.00	6.0–7.0	0.18–0.25	23.5–25.5	0.040	0.030	1.00	rem
N08904	904L	0.020	19.0–23.0	1.00–2.00	2.00	4.0–5.0	–	23.0–28.0	0.045	0.035	1.00	rem
N08926		0.020	19.0–21.0	0.5–1.5	2.00	6.0–7.0	0.15–0.25	24.0–26.0	0.030	0.010	0.50	rem

** Maximum unless a range is given.*

RURAL SITES

Locations categorized as “rural” are not exposed to industrial atmospheric discharges or coastal or deicing salts. Suburban areas with low population densities and light, non-polluting industry may also be categorized as rural. Both migrant air pollution and future development should be considered when categorizing a site.

Type 430 will suffer light to moderate staining and rusting on both exposed and sheltered surfaces. Smoother surface finishes and regular washing help reduce corrosion although some loss of brightness should be expected.

Type 304/304L exposed surfaces are virtually unattacked but sheltered surfaces could experience minor discolouration.

Smoother surface finishes provide better resistance to tarnishing and regular washing helps retain a pristine finish.

Type 316/316L with a smooth surface finish retains a bright appearance. Rougher surface finishes like a No. 3 or No. 4 polish may experience slight tarnishing. Washing is not generally necessary to maintain corrosion performance although dirt film removal improves appearance.

URBAN SITES

Urban sites include residential, commercial and light industrial locations with low to moderate pollution from vehicular traffic and similar sources.

Type 430 can become quite heavily rusted, especially in sheltered areas where pollutants

Table 6 Grade selection guidelines

Grade (Type)	Location											
	Rural/Suburb			Urban			Industrial			Marine/Deicing Salt		
	L	M	H	L	M	H	L	M	H	L	M	H
Highly Alloyed	■	■	■	■	■	■	■	■	●	■	■	●
316, 316L	■	■	■	■	●	●	●	●	(●)	●	●	(●)
304, 304L	●	●	●	●	●	(●)	(●)	(●)	✖	●	(●)	✖
430	●	(●)	(●)	✖	✖	✖	✖	✖	✖	✖	✖	✖

L *Least corrosive conditions within that category due to low humidity and low temperatures*
M *Fairly typical of category*
H *Corrosion is likely to be higher than typical for the category due to persistent high humidity, high ambient temperatures, and/or particularly aggressive air pollution*
■ *Good service, but may be over-specified*
● *Most economical choice*
✖ *Corrosion likely*
( ) *Indicates that the grade may be suitable if a smooth surface finish is selected and it is washed regularly*

Courtesy Allegheny Ludlum Corp.

Above the third floor, New York City's 150 East 42nd Street (completed in 1954) has Type 302 exterior wall panels with a 2B finish (surface roughness of R_a 15 micro inches or R_a 0.3 µm). Although their height protected them from deicing salt, they were exposed to pollution and coastal salt. They were cleaned for the first time in 1995, restoring their appearance. The Chrysler Building can be seen in the background. It is also Type 302 and has the same finish and surface roughness. It has been cleaned twice since 1930.

Courtesy J & L Specialty Steel

These Jones Beach, New York, street lights (installed in 1967) are Type 316 with a No. 4 polished finish. They are exposed to coastal and deicing salts.

Courtesy Alpha Manufacturing, Orlando, Florida

Type 316 toll booths are used in Massachusetts, New Jersey, Florida and where they are exposed to coastal salt, automotive pollution, and, in the northern states, deicing salt.

are not washed off by rain. Neither the surface finish nor regular washing has a significant effect on performance.

Type 304/304L can experience slight tarnishing. Regular washing will reduce this tarnishing. In most cases, smoother surface finishes provide better performance.

Type 316/316L performs well with little or no tarnishing. Regular cleaning is not strictly necessary to prevent corrosion but will improve the overall appearance by removing dirt.

INDUSTRIAL SITES

Industrial sites are locations with moderate to heavy atmospheric pollution usually in the form of sulphur and nitrogen oxides from coal combustion and gases released from chemical and process industry plants. Particulate deposits, such as soot from incompletely burned fuel or iron oxides, will increase the severity of the environment.

Type 430 is normally attacked quite severely. A smoother finish and/or periodic washing is unlikely to produce a significant improvement.

Type 304/304L will often suffer moderate to heavy attack although its performance can be improved by washing and selecting a smoother finish. In aggressive locations, upgrading to a more corrosion-resistant stainless steel may be appropriate. In less aggressive locations, Type 304 may be satisfactory if smooth finishes are selected, sheltered and low-slope or horizontal surfaces are eliminated to encourage natural rain washing, and supplemental washing is used as necessary to remove deposits.

Type 316/316L performs well in most locations. A light tarnish or staining may develop but can be minimized by regular washing and specifying smoother finishes. For extremely aggressive conditions, a more highly alloyed stainless steel may be needed.

COASTAL AND MARINE SITES

Seawater contains a mixture of salts. It is typically 2.5 to 4% sodium chloride with smaller quantities of magnesium chloride, calcium chloride, and potassium chloride. Chlorides in airborne sea spray and dry salt particles may cause pitting and rusting of stainless steels unless a sufficiently corrosion-resistant grade is chosen. Evaporation and infrequent rain increase salt concentrations on exterior surfaces and corrosion rates.

Humidity levels are a critical factor in determining corrosion potential. Each salt begins to absorb moisture and forms a corrosive solution at different critical humidity and temperature levels. See *Table 7*.[10] Corrosion is most severe at this critical humidity level because the solution is highly concentrated. The solution does not form at lower humidity or temperature levels.[11,12] High salt concentrations combined with high ambient temperatures and moderate humidity create the most aggressive conditions.

The distance airborne salt is carried can vary significantly with local wind patterns. In some locations, marine salt accumulations are only a factor within the first 0.9 miles or 1.5 km from the shore[3]. In other locations, salt may be carried much further inland. Japanese researchers found annual salt (sodium chloride) accumulations of 4.9 mg/dm^2/year at seaside, 3 mg/dm^2/year 984 feet (300 m) from the water, and

Table 7 Temperature and humidity levels at which selected marine and deicing salts begin to absorb water and form a corrosive chloride solution

Temperature		Critical Humidity Level		
°F	°C	Sodium chloride	Calcium chloride	Magnesium chloride
77	25	76%	30%	50%
50	10	76%	41%	50%
32	0	–	45%	50%

1.3 mg/dm^2/year 27 miles (50 km) inland.[13]

Figure 3 shows the average chloride concentration (mg/l) in rainfall across the United States. The chlorides in rainwater are primarily marine salts carried inland by weather patterns.[3] *Figure 4* shows the influence of deicing and marine salts, corrosive pollutants and particulate on North American vehicle corrosion and is equally relevant for street-level applications. SO_2 and NO_x can form sulfuric and nitric acid in the atmosphere and become acid rain. This does not show the severity of some west coast locations. US National Atmospheric Deposition Database chloride deposition data should be referenced. Deicing salt use has doubled since this map was developed expanding the size of the moderate and severe corrosion areas.

Generally, locations within five to ten miles (9 to 18 km) of salt water are considered at risk for chloride-related corrosion, but local weather patterns and the performance of metals near the site should be evaluated prior to material selection. To accelerate corrosion testing, most sites are on or near the coast because salt concentrations are higher.

Type 430 experiences severe rusting over a large proportion of its surface and is unsuitable for marine exposures.

Type 304/304L generally performs better than Type 430 but may experience severe pitting and should be used with caution.

Type 316/316L is commonly used for coastal architectural applications and will generally provide good service. A pristine appearance can usually be maintained by selecting a smooth surface finish and washing regularly to remove contaminants. If unwashed, some discolouration may occur after long-term exposure.

Type 316 may suffer unacceptable attack and a more highly alloyed stainless steel may be necessary under the following coastal conditions: high chloride salt deposition rates; proximity to a rocky shore; saltwater spray, splashing or immersion; regular high salt content light rain or salt fog; minimal annual rainfall; high particulate accumulation; or high levels of industrial pollution. In such cases, a corrosion specialist's advice is suggested.

DEICING SALT EXPOSURE

Typically, salt accumulations on handrails, doorstops, and other street-level applications are heavier in areas where deicing salt is used than in coastal locations. Deicing salt carried by road mist and wind has been found as high as the 59th floor of buildings and up to 1.2 miles (1.9 km) downwind from busy highways. The Nickel Institute article, “De-Icing Salt – Recognizing the Corrosion Threat”, provides more detailed information. *Figure 4* shows the impact of deicing salt use on motor vehicle corrosion and coastal exposure on street-level corrosion in North America.

Deicing salt is typically a mixture of calcium chloride and sodium chloride. Salt gradually begins to absorb water and forms a corrosive chloride solution at critical humidity and temperature levels. Corrosion is most severe at these threshold absorption levels because the solution is highly concentrated. When several salts with different critical humidity levels are combined, the temperature and humidity range at which corrosion can occur is broadened. Locations which combine the humidity and temperature ranges shown in *Table 7*[10] with high levels of deicing salt use and close proximity to the ocean have the greatest chloride corrosion risk.

Type 316 is usually suitable if there is a regular cleaning program to remove salt deposits. In particularly aggressive environments with high salt and pollution exposure, a more highly alloyed stainless steel may be needed.

The deicing salt damage visible on this welded Type 304L railing occurred after only one winter in Pittsburgh, Pennsylvania. Although there was some deicing salt used on the parking lot and stairs, the primary source of salt is a busy highway several hundred feet downhill from the building. Salt-laden road mist was blown onto the railing by the

Courtesy Technical Marketing Resources, Inc.

wind and deposited salt. The rough mill finish increased salt adherence. The discolouration was removed with a mild abrasive cleaner. Corrosion damage could have been avoided or minimized with frequent cleaning or selection of Type 316L with smooth finish.

Courtesy Technical Marketing Resources, Inc.

Figure 3 Average chloride concentration (mg/l) in rainwater in the United States and the eastern coast of Canada

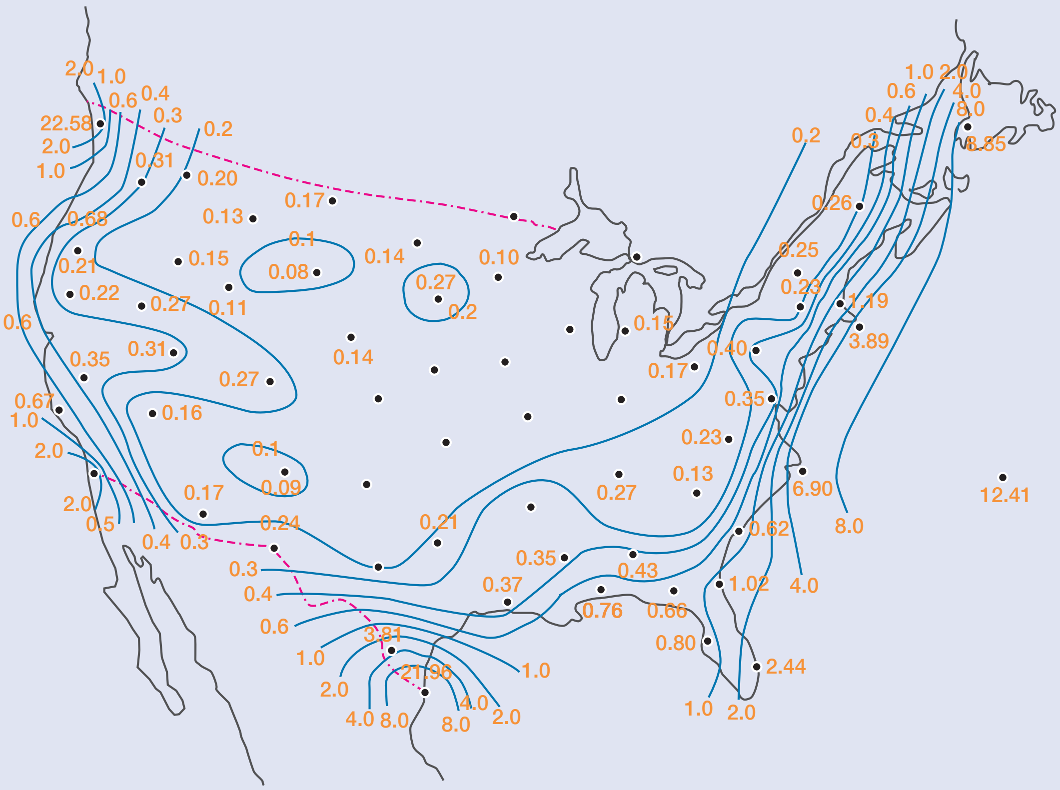
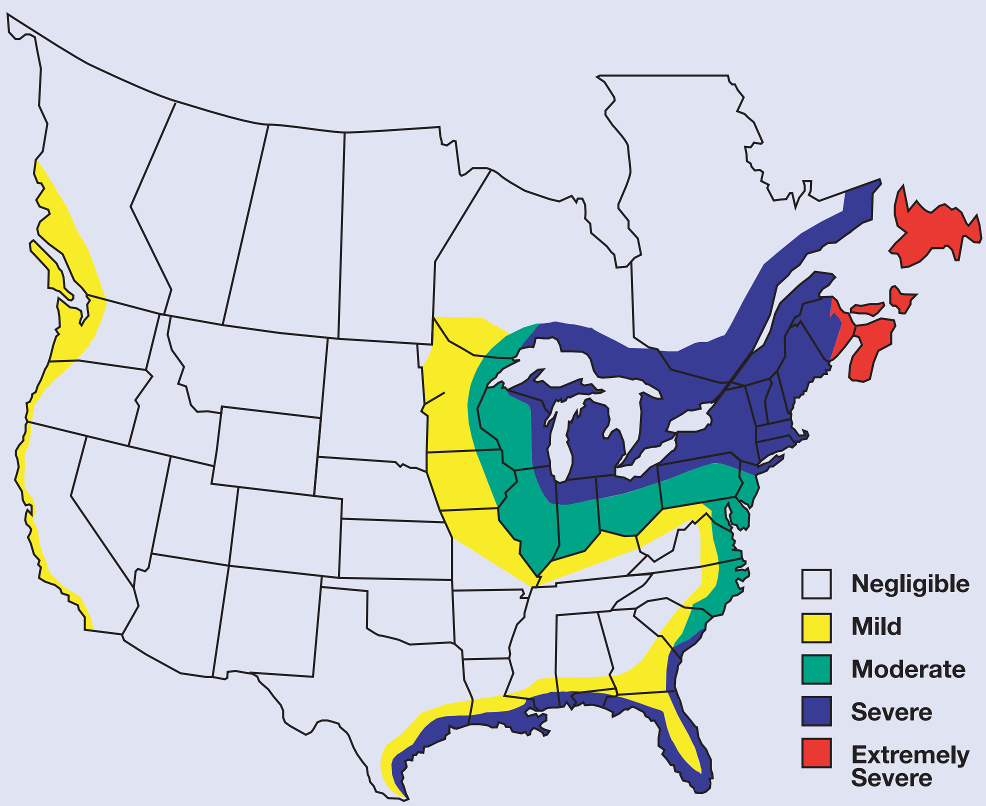


Figure 4 North American corrosion environment for vehicles and street-level applications



Courtesy Lohan Associates, Architect, and James Steinkamp, Steinkamp Ballogg Photography

Chicago's Blue Cross Building (completed in 1998) has Type 316 exterior wall panels for the first 30 feet to avoid deicing salt damage. The remaining panels are Type 304. The panels have a lightly coined finish that resembles fabric.

G. Stone for Nickel Institute

This highly polished Type 316 bike rack in Toronto, Ontario, is exposed to deicing salts and automotive pollution.

Table 8 Grade selection for roof applications

Environment	Rural and Suburban				Coastal, Industrial, Severe Urban			
Application	Roof or wall, rain washed		Eaves and under-eave wall, no rain washing		Roof or wall, rain washed		Eaves and under-eave wall, no rain washing	
Deposit Accumulation	No	Yes	No	Yes	No	Yes	No	Yes
S30400	●	■	■	▼	■	▼	▼	▼
S31600	●	●	●	■	●	■	■	▼
Highly alloyed	●	●	●	◆	●	◆	◆	◆

● *Suitable*
■ *Not suitable unless there are no corrosive deposits or deposits are removed by regular cleaning*
▼ *Unsuitable*
◆ *Suitability is dependent on the grade selected*

Table 9 Suggested cleaning frequency for Type 304 in different environments

Environment	Rural and Suburban				Coastal, Industrial, Severe Urban			
Application	Roof or wall, rain washed		Eaves and under-eave wall, no rain washing		Roof or wall, rain washed		Eaves and under-eave wall, no rain washing	
Deposit Accumulation	No	Yes	No	Yes	No	Yes	No	Yes
Suggested cleaning frequency (times/year)	0	1	1	2–12	1	1	3–4	4–12

Table 10 Comparison of atmospheric corrosion rates and pit depths in exposed and sheltered samples after 11.9 years' exposure in Bayonne, New Jersey

Grade	Composition, wt. pct.			Sheltered		Exposed	
	Cr	Ni	Other	Corrosion rate, mg/dm²/year	Pit depth, mils (mm)	Corrosion rate, mg/dm²/year	Pit depth, mils (mm)
317	18.6	14.1	3.5 Mo	0	<1.18 (<0.03)	0	0
316	17.8	13.1	2.8 Mo	0	<1.18 (<0.03)	0	0
304	18.4	8.9	–	22.63	7.09 (0.18)	0	0
430	17.1	0.3	–	10.95	7.87 (0.20)	0	0

Note: The test samples were mounted vertically in sheltered and in boldly exposed orientations.

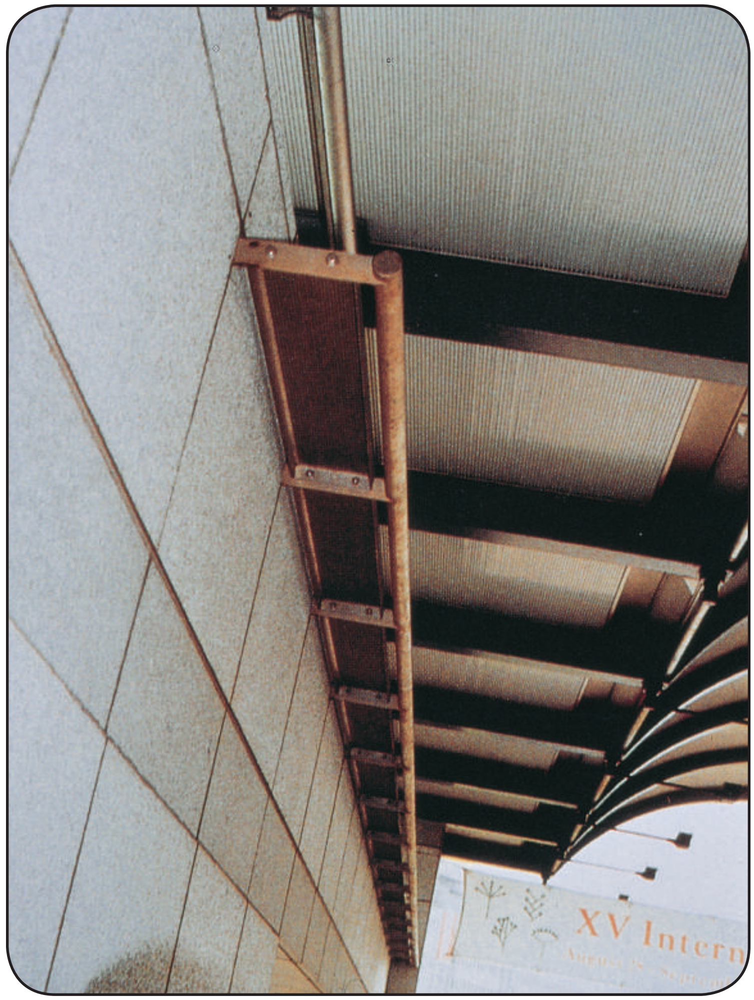
SHELTERED EXTERIOR APPLICATIONS

Atmospheric dust frequently contains corrosive sulphides, marine salts, deicing salt, iron oxide, and other contaminants. If sheltered areas, such as building eaves, are not cleaned regularly, dust accumulates, creating a more aggressive corrosion environment.[15] The presence of chlorides and moderate levels of humidity may facilitate corrosion of a susceptible stainless steel or other metals in sheltered applications. See *Table 7*. Sheltered locations, like building eaves, tend to have more moderate humidity levels than exposed locations, thereby adding to the corrosiveness of those environments.[15]

The suggested grades (*Table 8*) and cleaning frequency (*Table 9*) are based on Japanese research on sheltered locations.[16] *Table 10* shows the corrosion rates and pit depths for various stainless steels after 11.9 years in Bayonne, New Jersey, a polluted, coastal location, and illustrates the beneficial effect of increasing chromium and molybdenum.[17] Although the corrosion rates of some of the exposed samples were the same, differences in appearance were observed.

ATMOSPHERIC CORROSION COMPARISONS

Atmospheric corrosion tests have been conducted in many parts of the world to compare the performance of metals in different environments. These data are helpful in selecting appropriate metals for similar environments and preparing life-cycle cost analyses. Although the same average corrosion rates were measured for stainless steels with different levels of corrosion resistance in some geographic locations, NI stock photo



Corrosion of unwashed stainless steel pipes sheltered by building eaves.

C. Houska for NI

The polished Type 302 former Toronto Stock Exchange doors (installed in 1936) are exposed to pollution and deicing salt. Minor pitting occurred when they were neglected for several years. They were restored and regular cleaning keeps them attractive now.

Table 11 Average corrosion weight loss in mils/year (mm/year) at Japanese sites after four or five years' exposure

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 were exposed for four years.*

appearance differences were observed. These appearance differences were incorporated into the grade selection guidelines in *Table 6*.

The corrosion weight loss of carbon steel, weathering steel, Type 304, and aluminum were measured after either four or five years' exposure at seven coastal, inland, and industrial sites in Japan. The results are summarized in *Table 11*.[18]

Tropical environments can range from arid deserts to humid, industrial sites. The U.S. Naval Research Laboratory in Washington, D.C. conducted a 16-year study of 54 metals at two sites in Panama. The Miraflores site is 4.3 miles (8 km) from the coast in a semi-urban location with prevailing winds from the land to the ocean. The Cristobal site is a marine location on a roof 52 feet (16 m) above the shore, facing wind from the ocean. In both locations, the panels were angled 30 degrees from the horizontal. See *Table 12*.[19]

In the United States, extensive marine testing of metals has been conducted at Kure Beach, North Carolina. *Table 13* compares the average corrosion rates of Types 304 and 316 with carbon steel, Galvalume®, and galvanized steel.[3,20]

Various architectural metals have been tested at six

Table 12 Atmospheric corrosion data for two tropical sites in Panama

Constituent mg/10m³	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 and volatile matter	6.07	0.56	2.61	2.44	0.39	1.20
Sulphate	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	<0.01 (<0.0003)	<0.01 (<0.0003)	<4.92 (<0.125)	0 (0)	0 (0)	<4.92 (<0.125)
Aluminum 1100	0.11 (0.0028)	<0.01 (<0.0003)	<4.92 (<0.125)	0.07 (0.0019)	<0.01 (<0.0003)	<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 (99.9%)	0.20 (0.005)	<0.01 (<0.0003)	<4.92 (<0.125)	0.09 (0.0024)	<0.01 (<0.0003)	<4.92 (<0.125)
Alloy 400	0.22 (0.0056)	<0.01 (<0.0003)	<4.92 (<0.125)	0.14 (0.0036)	<0.01 (<0.0003)	<4.92 (<0.125)
Cartridge brass	0.33 (0.0084)	0.02 (0.0005)	<4.92 (<0.125)	0.25 (0.0063)	<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)
Muntz metal	0.43 (0.011)	0.03 (0.0008)	<4.92 (<0.125)	0.32 (0.0081)	<0.01 (<0.0003)	<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 (0.940)

Table 13 Average corrosion rates 250 m (800 ft) from mean high tide at Kure Beach, North Carolina		
Metal	Exposure time, years	Avg. corrosion rate, mils/year (mm/year)
Type 316	15	<0.001 (<0.000025)
Type 304	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 14 Average annual corrosion rate after 20 years' exposure in South Africa

	Pretoria-CSIR	Durban Bay	Cape Town Docks	Durban Bluff	Walvis Bay	Sasolburg
Environment						
Location Type	rural, very low pollution	marine, moderate pollution	marine, moderate pollution	severe marine, moderate/low pollution	severe marine, low pollution	industrial, high pollution
SO_2 Range µg/m³	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
Stainless steels	Annual Corrosion Rate mils/year (mm/year)					
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)	0.02 (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
AA 96082	0.01 (0.00033)	0.14 (0.00366)	0.13 (0.0034)	1.09 (0.02761)	0.23 (0.00587)	NA
AA 96261	NA	NA	NA	0.93 (0.02364)	0.15 (0.00375)	0.12 (0.00317)
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)
Weathering steel	0.9 (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)

Life in years = defined as red rust on 5% of the surface area
NA = data was not available for this site

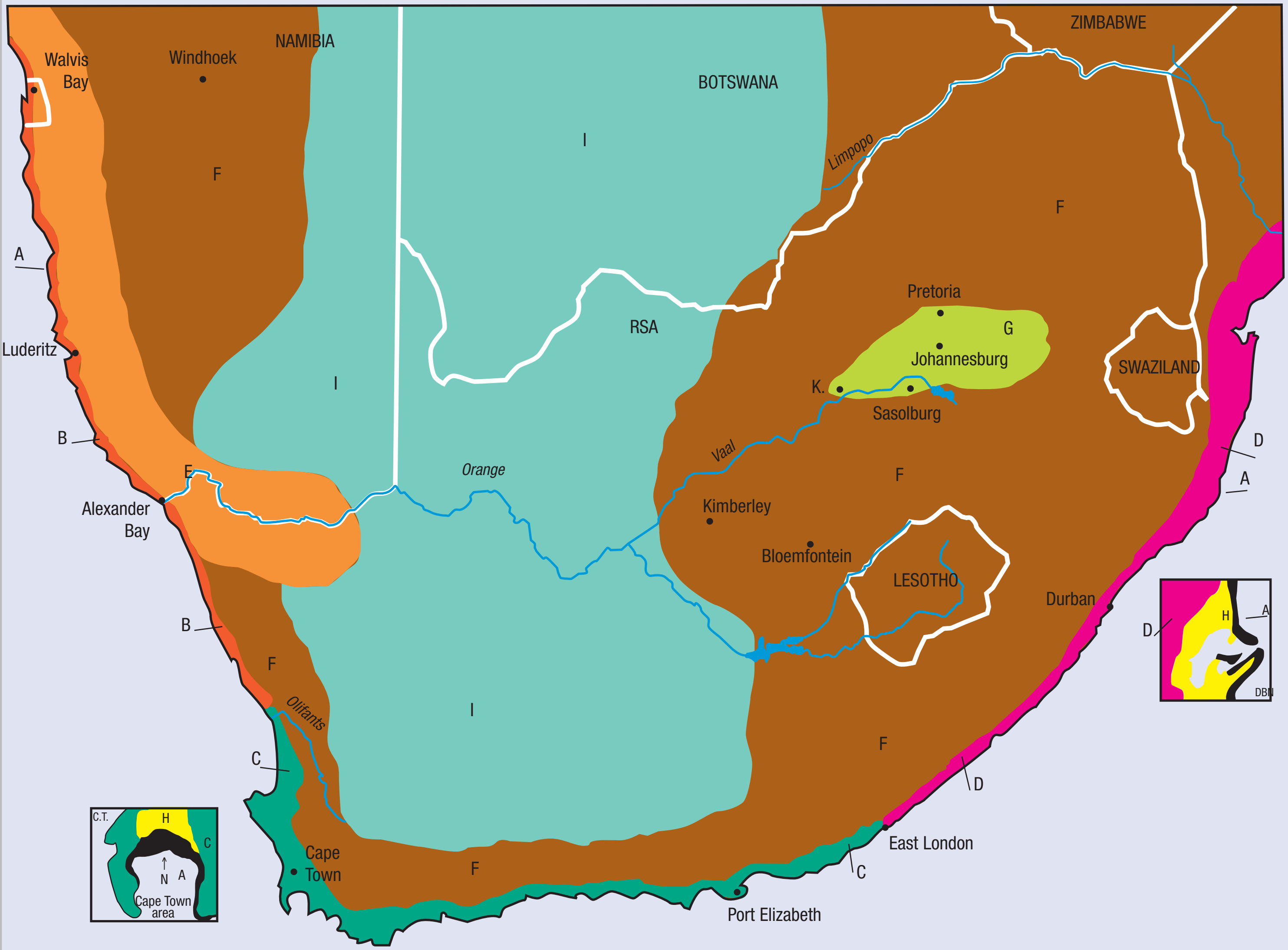
test sites in South Africa. *Table 14* and *Figure 5* show the characteristics of each site and the average annual corrosion rate of mild steel and the service life of galvanized steel in years, in the twenty-year test program.[21]

MECHANICAL PROPERTIES AFTER LONG-TERM ATMOSPHERIC EXPOSURE

In some architectural applications, stainless steel is a load-bearing member. Samples of austenitic stainless steels were exposed at 25 and 250 metres from the mean high tide in a marine, coastal location in North Carolina, U.S.A. to determine if long-term atmospheric exposure affected their strength.

After 26 years' exposure to wind-blown salt spray, rain and hurricanes, tensile tests were performed and the strength and ductility were compared with identical samples that had been stored indoors. Similar tests were conducted at a coastal site in India with a ten-year exposure. The austenitic 300-series steels had no significant change in strength or ductility after long-term exposure in these aggressive coastal environments.

Figure 5 Atmospheric corrosion map of South Africa



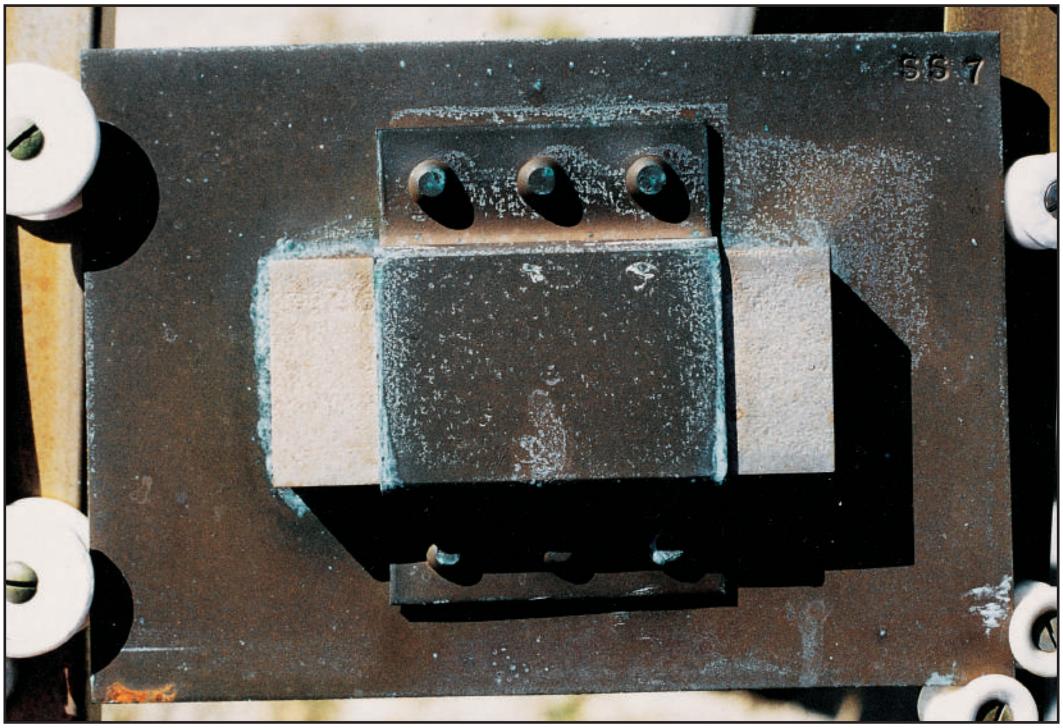
LEGEND

Code	Description	Map identif.	Type of corrosion	Mild steel* corrosion rate µm/yr	Galvanized steel sheet** life in years†
A	Intertidal to 5 km inland	(black)	Severe marine	100 – 300	Up to 3
B	Desert marine (mists)	(red)	Severe marine	80 – 100	0.5 – 2
C	Temperate marine	(green)	Marine	30 – 50	3 – 7
D	Subtropical marine	(magenta)	Medium to severe marine	50 – 80	3 – 5
E	Desert inland dry	(orange)	Desert	< 5	> 30
F	Inland	(brown)	Rural	10 – 20	> 20
G	Inland urban	(light green)	Inland industrial††	15 – 40	5 – 15
H	Urban coastal	(yellow)	Marine industrial††	50 – 150	1 – 3
I	Inland arid	(turquoise)	Semi desert	5 – 10	> 30

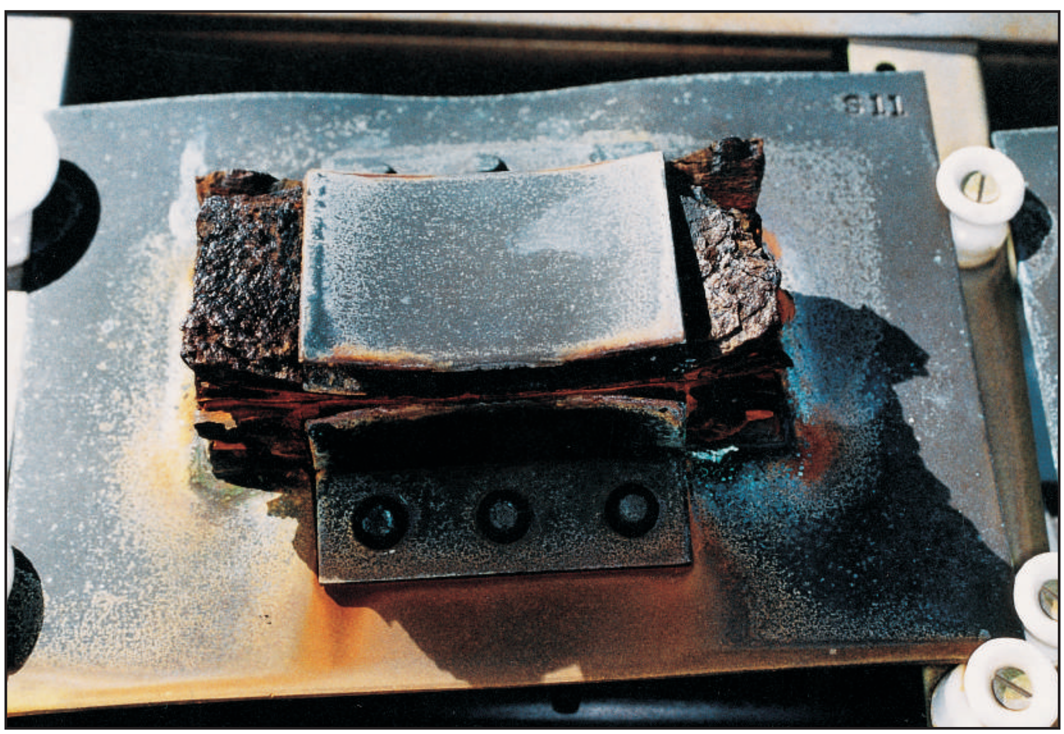
* Higher corrosion rate usually indicates proximity of sea.
** Commercial grade Z 275 g/m^2 (unpainted)
† Life in years – until 5% of surface area showing red rust.
†† Industrial implies pollution present in atmosphere.
C and D usually from 5 km inland up to first mountain range.

ATMOSPHERIC CORROSION SAMPLE PHOTOS

The atmospheric corrosion test samples shown in the following 13 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 820 feet (250 m) from the ocean's mean high tide. These photos were taken in 2000.



Type 316 stainless steel and copper combination is performing well.



The mild steel plate's corrosion product has expanded and broken the copper saddle.

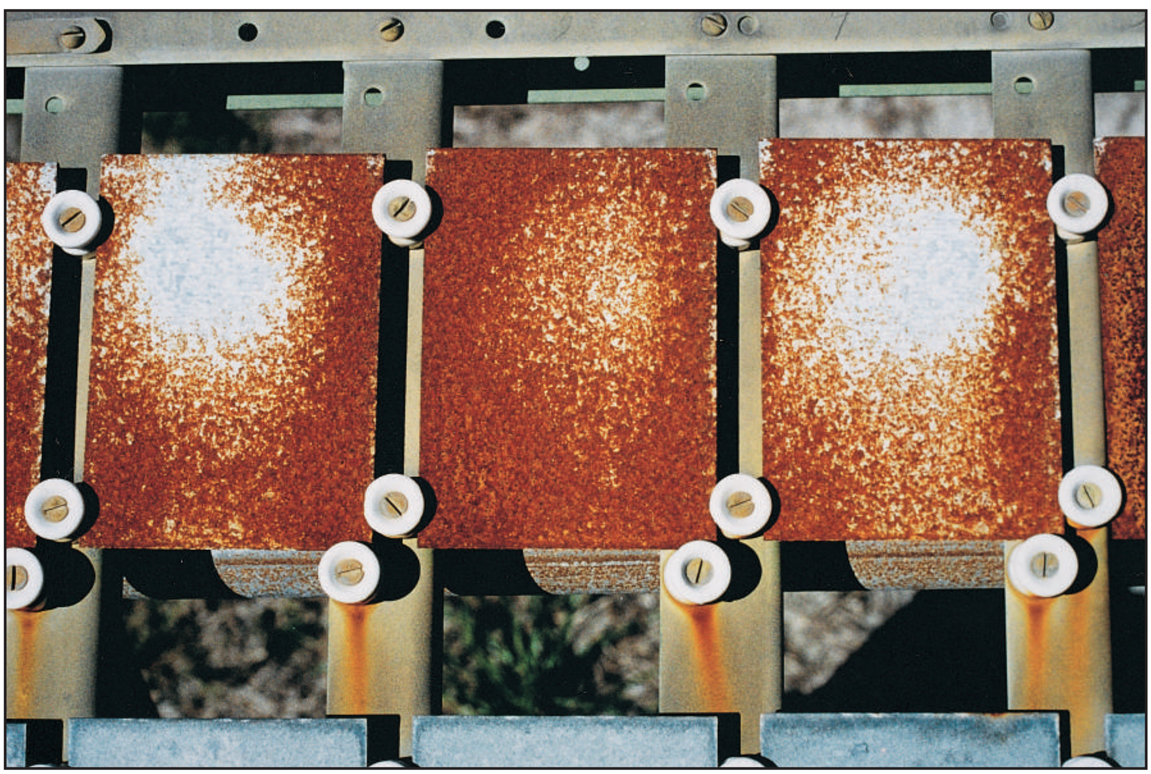
The above Statue of Liberty corrosion demonstration panels have been in place since 1984. Type 316 and carbon steel plate samples were attached to copper sheets with a saddle which is riveted in place.

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

Painted cast aluminum alloy 360 exposed since 1988.

Anodized aluminum exposed since 1942.

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



Bare G-90 galvanized steel exposed since 1981.

Painted cold rolled steel exposed since 1988.

High-strength, low-alloy weathering steel exposed since 1968.

Type 304 exposed since 1941.

Type 316 exposed since 1941.

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

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

FORMS OF STAINLESS STEEL CORROSION

If stainless steel is selected, installed, and maintained correctly, it does not suffer corrosion. However, if the environment exceeds the corrosion resistance of a particular stainless steel in a specific location, some corrosion may occur. Only certain types of corrosion may affect stainless steels.

TARNISHING

Tarnishing is a fairly uniform discolouration of a metal's surface. With exterior stainless steel applications, there may be a slight yellow tarnishing of the surface and some loss of brightness, especially if fine particles of dirt are incorporated into the surface deposit. Some improvement may be obtained from washing but the overall effect on appearance is small and may not be apparent when viewed from a distance.

PITTING

If a stainless steel corrodes, pitting is the most likely form of corrosion. If the environment overwhelms the capability of the stainless steel, the protective, passive film is disrupted and cannot heal itself. This is shown schematically in *Figure 6*. (See Atmospheric Corrosion Section.) Pitting starts as tiny points of attack and is usually black or dark brown in colour. In the most severe cases, the number and depth of the pits can increase to give an extensively corroded appearance. If the attack is mild, the pits may not detract from the general appearance but the area below them may be stained as rust leaches out. Selecting an appropriate stainless steel and cleaning regularly to remove surface deposits reduce the potential of pitting damage.

CREVICE CORROSION

Crevice corrosion is similar to pitting but occurs over a larger area when deposits or other materials block the oxygen access needed to maintain the passive film. Corrosion can occur if salt and moisture (rainwater, humidity, fog or condensation) is present in a tight crevice. It is more likely with lower-alloyed stainless steels, particularly where the crevice gap is very small such as under a fastener head, in a rolled joint or between overlapping pieces of metal. Correct design reduces the potential for crevice corrosion. In water shedding applications, designers should avoid crevices, seal them (welding, sealant or a flexible inert washer), or consider a more corrosion-resistant, higher-alloyed grade. Flexible inert washers are not suitable for curved surfaces or immersed applications. See *Figure 7*.

GALVANIC CORROSION

Galvanic or "bimetallic" corrosion can occur when two metals of differing electrochemical potential are electrically coupled in a conducting liquid, usually called an electrolyte. Several factors determine galvanic corrosion potential: the

Figure 6 Pitting corrosion

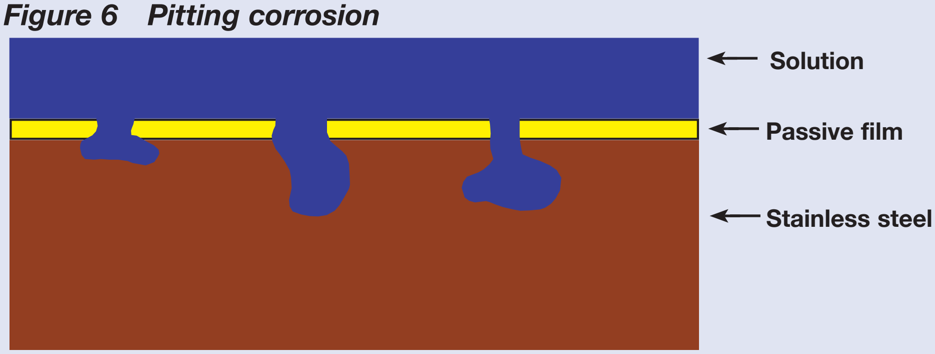
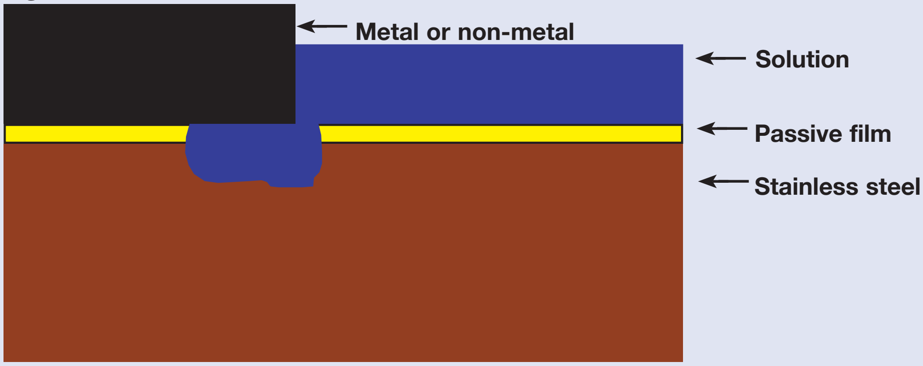


Figure 7 ***Crevice corrosion***



electrochemical potential difference, the presence of moisture to connect the metals on a regular basis, and the relative surface area ratio of the metals. If no moisture is present or an inert, electrically insulating material prevents electrical contact, galvanic corrosion cannot occur.

Figure 8 illustrates galvanic corrosion. *Figure 9* shows examples of when galvanic corrosion can and cannot occur. *Figure 10* shows the galvanic series in seawater. The metals are arranged in order from the least noble (least corrosion-resistant) to the most noble (most corrosion-resistant).

Galvanic corrosion may be a concern if there is a significant difference in electrochemical potential and the metals are not electrically isolated from one another. If two metals are close together in the galvanic series (e.g., two stainless steels or copper and stainless steel), the potential for galvanic corrosion is low in all but the most aggressive environments.

The relative surface area of the two metals is important. When the surface area of the more corrosion-resistant metal is large relative to the less corrosion-resistant metal, an unfavourable ratio exists and there is an increase in the corrosion rate of the less corrosion-resistant metal. For example, coupling a small piece of carbon steel to a large piece of stainless steel could cause rapid corrosion of the carbon steel. If the ratio is reversed and the less corrosion-resistant material has a large surface area, the corrosion rate of the less corrosion-resistant metal is only slightly increased.

Dissimilar metal combinations should be avoided in areas where moisture is likely to accumulate and remain for long periods. In well-drained exterior applications, dissimilar metals can be used together if a favourable surface ratio exists, but they should be electrically insulated from one another. Neoprene washers, roofing felt, paint, and other inert materials or coatings are effective barriers. When painted carbon steel and stainless steel are welded together in an exterior application, the welded joint should be painted. Hidden and exposed stainless steel fasteners with neoprene or other inert washers are used regularly in aluminum, zinc, and painted galvanized steel roof applications. The inert washer separates the metals in case water is frequently present or infiltrates under the head of the fastener.

Figure 8 ***Galvanic corrosion***

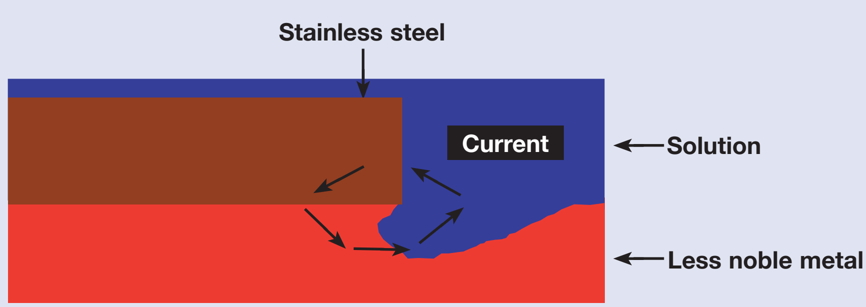


Figure 9 Dissimilar metal and electrolyte combinations where galvanic corrosion can and cannot occur

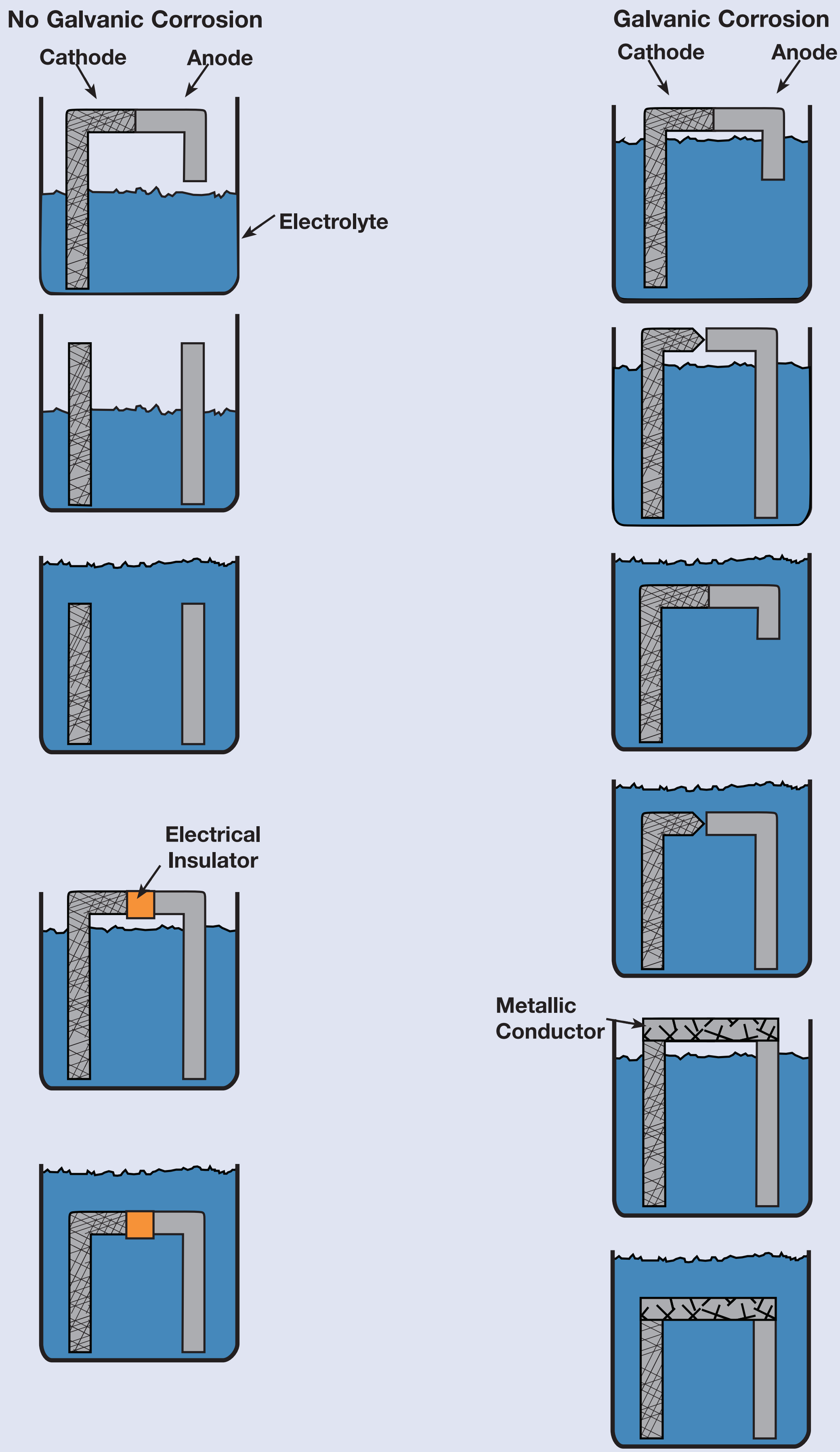


Figure 10 Galvanic series in seawater at 77°F (25°C) [22]

Least noble = anodic = most susceptible to corrosion

Magnesium and its alloys
Zinc
Galvanized steel or galvanized wrought iron
Aluminum alloys 3004, 3003, 1100, in this order
Cadmium
Low carbon steel
Wrought iron
Cast iron
Nickel cast irons
50-50 lead-tin solder
Lead
Tin
Muntz metal, C28000
Yellow brass, C27000
Aluminum bronzes, C61400
Red brass, C23000
Commercially pure copper, C11000
Silicon bronze, C65500
Alloy 200
Alloy 600
Alloy 400
Stainless steel, Type 410
Stainless steel, Type 304
Stainless steel, Type 316
Alloy 825
Alloy 625
Alloy C
Silver
Titanium
Gold

Most noble = cathodic = most corrosion-resistant

EMBEDDED OR TRANSFERRED IRON

Iron or carbon steel can become transferred to or embedded in the surface of stainless steel and other architectural metals and begin to rust within a few hours or days. This can give the incorrect impression that the material underneath is rusting. However, in severe cases, the rusting steel may actually cause the stainless steel under it to corrode because the protective passive film cannot re-form.

The source of iron can be steel tools, abrasive polishing or blasting media or fabrication areas previously used on carbon or low-alloy steels, use of carbon steel wool or carbon steel brushes during cleaning, and accidental scratching. Ideally, the fabrication area should be dedicated to stainless steel. If that is not possible, the area should be cleaned prior to stainless steel fabrication to remove residual iron particles. To prevent accidental contamination, the stainless steel surface should be protected with protective paper or strippable plastic films during fabrication, handling, storage and transport.
The purchaser can specify that stainless steel products pass one of several non-destructive tests for detection of embedded iron such as ASTM A 967. A particularly simple and straightforward test is to thoroughly wet the surface with clean water and wait for 24 hours to see if rust appears. Additional information about preventing, detecting and removing embedded iron and steel can be found in the Nickel Institute publication, *Fabrication and post-fabrication cleanup of stainless steels, No. 10 004.*

EROSION-CORROSION

Erosion-corrosion is accelerated metal loss caused by a flowing corrosive liquid which contains abrasive particles such as sand or debris. It can be a problem with aluminum, copper and other susceptible materials in applications like piping and roof drainage systems. Resistance to erosion-corrosion is not related to hardness or strength, but flow velocity, high turbulence, or changes in flow direction can have a significant impact on performance in susceptible metals.[23] Stainless steels are virtually immune to erosion-corrosion because they form thin, tightly adherent, protective passive films. High flow velocities are beneficial to stainless steel corrosion performance because they help keep the stainless steel surface clean.

CHLORIDE STRESS CORROSION CRACKING, (SCC)

Chloride stress corrosion cracking (SCC) may occur in Types 304 and 316 exposed to chlorides and tensile residual stress at temperatures above about 150˚F (65˚C). These conditions are unlikely in most architectural applications.

SCC has occurred at lower temperatures in unusually severe indoor environments, such as swimming pool suspended ceilings. The Nickel Institute publication No. 12 010, *Stainless steel in swimming pool buildings*, and Nickel Institute article *Successful Stainless Swimming Pool Design* provides additional information about appropriate grades for this application. The potential for SCC in an aggressive marine environment was evaluated in a five-year study of 300-series stainless steels in three metallurgical conditions: annealed (the normal as-delivered mill condition), as welded, and cold-worked. The site for these tests, Kure Beach, North Carolina, U.S.A., experiences hot summers. The underside of the panels reached temperatures of about 120˚F (50˚C) and the exposed side 140˚F (60˚C).[24] None of the samples experienced stress corrosion cracking.

C. Houska for NI

This infrequently cleaned statue of Sun Yat Sen (installed in the 1930s) in San Francisco's Chinatown combines stainless steel (body) and copper (hands and head). Moisture is only present for short periods of time. The two metals are in close proximity in the galvanic series and there is no sign of galvanic corrosion.

C. Houska for NI

The ratio between the dissimilar metals is important in evaluating the potential for galvanic corrosion. The fastener should always be of equivalent or higher corrosion resistance. Stainless steel fasteners with inert washers are often used for Weathering steel (left), carbon steel, copper aluminum and zinc roof and wall panels. Galvanized steel fasteners should never be used for stainless steel panels. (below).

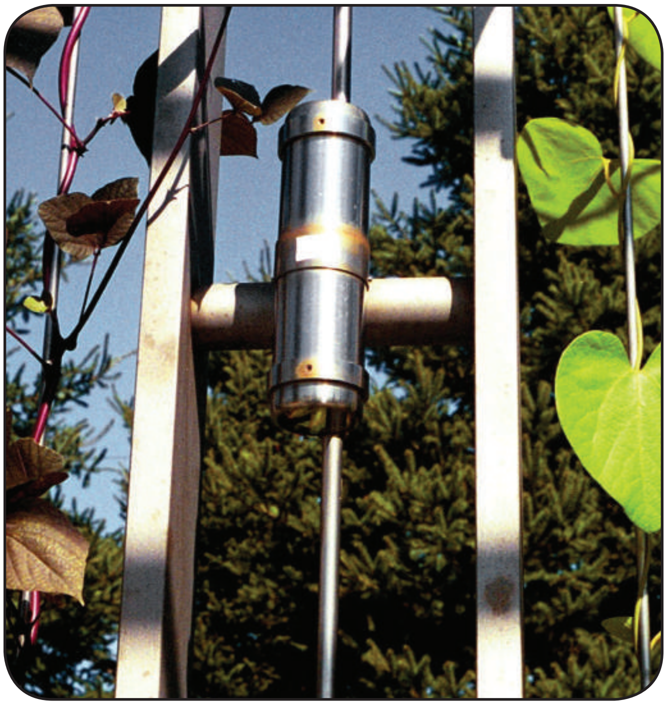
ENVIRONMENTAL BENEFIT OF STAINLESS STEEL

The environmental impact of construction materials is a growing concern. If an appropriate grade and finish are selected, there should be no need to replace stainless steel, even if the building life spans hundreds of years. Stainless steel scrap has a high value – so it is not discarded. Stainless steel is 100% recyclable and there is no limit to how much recycled scrap can be used to produce new stainless steel.

Metal loss due to corrosion can potentially add toxic elements to the environment and the lost metal cannot be recycled. Replacing lost metal adds an additional environmental burden (energy consumption, mining, mineral extraction). Stainless steel corrosion loses are negligible. (See comparative corrosion data.)

Because stainless steels are inherently corrosion-resistant, no protective coatings are needed, and the adverse environmental impact associated with coatings (out-gassing of volatile organic compounds [VOC], replacement, and removal for recycling) is eliminated. No acids or harsh chemicals are needed to clean stainless steel.

Stainless fasteners and anchors help ensure that stone, masonry, pressure-treated lumber, slate, and tile reach their full service life potential.



A

B

C

C. Houska for NI

Careful evaluation of a site is important because factors that influence the corrosiveness of a site may not be immediately apparent. This stainless steel arbour is in a park in a suburban area adjoining downtown Minneapolis. Normally a location of this type would be considered a low to moderately corrosive urban environment, but this park is beside an elevated highway and deicing salt laden road mist blows into the park, making the environment more aggressive.

All the arbour's components are rough, abrasive blasted Type 304 (surface roughness of R_a 281 micro-inches or 7.3 μm) except for the tension rods and lights which are highly polished Type 316. Photo A shows Type 304 deicing salt damage. The rough finish retains more salt, making natural rain washing less effective. Sheltered surfaces experienced significantly more corrosion than components boldly exposed to rain. The Type 316 was untouched by the deicing salt except where crevices trapped salt and water. Photo B shows crevice corrosion. Photo C shows embedded iron on one of the Type 304 vertical support members.

Corrosion of the attractive design could have been avoided if the entire arbour were Type 316 with a smooth finish, crevices were sealed or eliminated, salt had been washed off the arbour in the spring, and the surfaces were protected from embedded iron during transport, fabrication and installation.

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TRADE NAMES

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