suspected. According to the report, it is desirable to have no detectable soluble salts present on the surface to be coated; however, there is a cost associated with their detection, removal, and confirmation of removal by retesting. These associated surface-preparation costs provide an incentive for risk assessment to balance the cost-to-benefit ratio of reducing levels or removing salts that may be present. Guidance levels are cited in papers prepared by several researchers; however, until industry standards are developed, guidance should be obtained from the coatings manufacturer, based on the prevailing service environment and the type of coating system to be applied.

Methods of Surface Preparation

Surface-preparation methods can range from simple solvent cleaning to hand and power tool cleaning, dry and wet abrasive blast cleaning, chemical stripping, waterjetting, and nontraditional methods such as sponge jetting and cryogenic blast cleaning using dry ice pellets. Each of the traditional methods is briefly summarized subsequently, together with reference to the applicable SSPC standard. A description of the SSPC standards is found in the final section of this article.

Solvent cleaning involves the use of solvents to remove visible deposits of grease and oil from the surface. Organic contaminants such as grease, oil, cutting compounds, or lubricants can be removed by using solvents such as methyl ethyl ketone, xylene, or proprietary cleaners sold by coating manufacturers. Other cleaning methods include steam (with or without a cleaning compound or detergent) or pressure washing with a cleaning compound or detergent capable of dissolving the contamination. The industry standard for solvent cleaning is SSPC-SP 1, “Solvent Cleaning.”

Hand tool cleaning is typically performed with wire brushes, scrapers, sandpaper, and other tools that do not depend on electric or pneumatic power to operate (Fig. 21). These hand tools are intended only to remove loosely adhering corrosion products, old paint, and flaking mill scale and are not intended to produce an anchor pattern in the steel. Hand tools are frequently used to prepare surfaces for spot touchup during maintenance painting activities. The industry standard for hand tool cleaning is SSPC-SP 2, “Hand Tool Cleaning.”

Power tool cleaning is typically performed with grinders, cup wire brushes, Bristle Blasters (Montipower, Inc.), sanders, pneumatic chisels, needle scalers, and rotating flap tools that require an electric or pneumatic power source to operate (Fig. 22, 23). Most of these tools can remove both loosely and tightly adhering corrosion products, rust scale, paint, and mill scale from steel surfaces. Some of these tools can also produce an anchor pattern in the steel by peening the surface. Additionally, these tools can be purchased with vacuum ports and hoses for attachment to high-efficiency particulate-air-filtered vacuums so that the fine airborne particles that are generated during surface-preparation activities are collected at the point of generation. This is specifically useful when removing coatings that contain lead or other toxic metals. There are several industry standards for power tool cleaning based on the amount of material to be removed: SSPC-SP 3, “Power Tool Cleaning”; SSPC-SP 11, “Power Tool Cleaning to Bare Metal”; and SSPC-SP 15, “Commercial-Grade Power Tool Cleaning.” ISO 8501-1, “Pictorial Surface Preparation Standard for Painting Steel Surfaces,” contains two degrees of hand and power tool cleaning, including St2, “Thorough Hand and Power Tool Cleaning,” and St3, “Very Thorough Hand and Power Tool Cleaning.”

Dry Abrasive Blast Cleaning. Blast cleaning using dry abrasive media (Fig. 24) is a very common method of preparing a metal surface for coating. Abrasive blast cleaning can be used to roughen an existing coating for subsequent overcoating or to completely remove the existing corrosion products, coating, and mill scale. Abrasive blast cleaning is the most productive of all surface-preparation methods. Thousands of square feet of surface can be prepared for coating in a single work shift. The hardness and mass of the abrasive medium combined with the velocity of the abrasive as it exits a nozzle at speeds up to 800 kph (500 mph) (using air pressures up to 0.9 MPa, or 125 psi) generate high levels of energy. As the abrasive medium impacts the surface with this energy, it can remove existing coating layers, corrosion, and mill scale, simultaneously increasing the surface area of the steel by generating a surface


Fig. 22 Bristle Blaster power tool used to perform power tool cleaning. Photo used with permission from Montipower, Inc.


Fig. 21 Wire brush used to perform hand tool cleaning


Fig. 23 Rotating flap, needle scaler, and nonwoven fiber wheel used to perform power tool cleaning


Fig. 24 Open-nozzle abrasive blast cleaning. Photo used with permission from SSPC: The Society for Protective Coatings

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profile or anchor pattern. The depth and shape of the surface profile is determined by the type and size of the abrasive medium employed, as well as the hardness of the surface being prepared. Therefore, selecting the correct type and size of abrasive is critical. Selecting too small an abrasive size may generate a surface profile that is too shallow for the coating to be applied, and selecting too large an abrasive may create a surface profile that is too deep.

A traditional dry abrasive blast-cleaning setup consists of a source of compressed air (of sufficient capacity to provide an adequate volume of air to support the nozzle size, hose length, air pressure, and number of operators), an American Society of Mechanical Engineers-coded abrasive hopper equipped with an air moisture and oil separator, a metering valve (located at the base of the hopper to meter abrasive from the hopper into the blast hose), a blast hose to carry the metered abrasive and compressed air to the nozzle (equipped with external hose couplings, safety wires and/or cables, or whip checks), and a blast nozzle. Projects employing recycled abrasives typically use blast pots in conjunction with vacuum equipment for collecting spent abrasive, and recycling equipment for separating the smaller particles and debris from the reusable abrasive.

There are a variety of abrasives that can be used in the blast-cleaning process. They fall into two broad categories: expendable and recyclable. Expendable abrasives are used once and then discarded, because the breakdown rate is relatively high. In contrast, the breakdown rate of recyclable abrasives is relatively low, allowing them to be used multiple times before they are discarded. For example, a recyclable steel grit abrasive can be reused more than 100 times with minimal breakdown.

Expendable abrasives fall into two general categories: mineral and slag. Mineral abrasives are naturally occurring and include silica sand, garnet, and staurolite sand. Slag abrasives are not naturally generated but represent by-products of other industries that are processed into abrasives. These include copper, coal, and nickel slag. Corncobs and walnut shells are also naturally occurring and can be used as polishing abrasives. However, these agricultural abrasives are not considered aggressive enough to remove industrial protective coatings and are not hard enough to generate a surface profile in steel. The SSPC abrasive specification No. 1 (SSPC-AB 1), "Mineral and Slag Abrasives," defines the qualification requirements for mineral and slag abrasives used for blast cleaning. These requirements are listed in Table 1.

Recyclable abrasives generally include steel grit, steel shot, and aluminum oxide. Steel grit and aluminum oxide (as well as all of the expendable media listed previously) are considered angular, which means they contain sharp points that in turn produce sharp peaks and valleys in the surface (Fig. 25). These increase the surface area of the steel as a result of the density of the peak pattern (the peaks are close together and there are many of them). Steel shot (Fig. 26) is considered a round or spherical abrasive that produces a rounded profile or a peened surface texture, which results in a comparatively lower peak density pattern, because the peaks are round, farther apart, and fewer. Some coating systems (such as thermal spray coatings) rely heavily on a mechanical bond to the surface and cannot tolerate a peened surface texture. However, most liquid-applied coatings adhere sufficiently to both angular and rounded surface profile patterns. The SSPC abrasive specification No. 3 (SSPC-AB 3), "Ferrous Metallic Abrasive," defines the requirements for steel abrasives used for blast cleaning, and SSPC abrasive specification No. 2 (SSPC-AB 2), "Cleanliness of Recycled Ferrous Metallic Abrasives," defines the cleanliness requirements for recycled blast-cleaning abrasive.

Table 1 SSPC-AB 1 abrasive qualification requirements

Qualification test	Industry standard reference
Specific gravity	ASTM C128
Hardness	Not indicated
Weight change on ignition	Not indicated
Water-soluble contaminants	ASTM D4940
Moisture content	ASTM C566
Oil content	ASTM D7393
Crystalline silica content	NIOSH method 7603(a)
Surface profile	ASTM D4414 and SSPC-PA 17
Particle size distribution	ASTM C136
Health and safety requirements	Not indicated

(a) NIOSH, National Institute for Occupational Safety and Health

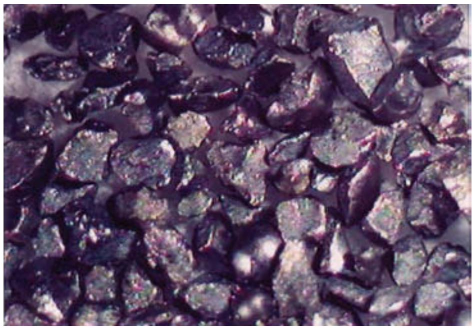

Fig. 25 Angular abrasive

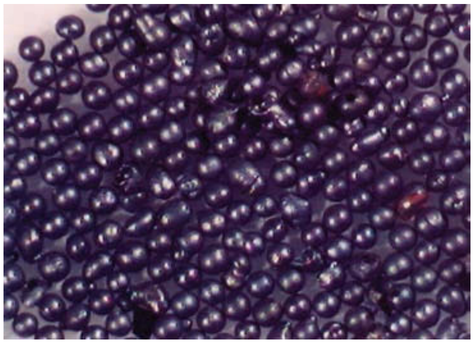

Fig. 26 Round abrasive

The SSPC-AB 3, "Ferrous Metallic Abrasive," contains performance requirements (Table 2) that the abrasive manufacturer must conduct and report on prior to publishing that the abrasive meets the standard.

The SSPC-AB 4, "Recycled Encapsulated Abrasive Media," defines performance requirements (Table 3) for recyclable encapsulated abrasive media consisting of steel grit, aluminum oxide, or mineral abrasives in a compressible open-cell matrix (sponge) (Fig. 27a). It requires specialized equipment and is used when dust control is a priority (Fig. 27b).

Standards addressing different degrees of abrasive blast cleaning in order from the least amount of cleaning to the most are SSPC-SP 7, SSPC-SP 14, SSPC-SP 6, SSPC-SP 10, and SSPC-SP 5.

Centrifugal Wheel Blast Cleaning. Centrifugal or automated abrasive blast cleaning can be performed using portable (Fig. 28) or stationary (Fig. 29a) equipment. Portable centrifugal blast machines can be used to prepare floors in warehouse facilities, ship decks, and other large, flat surfaces. They can also be mounted to vertical surfaces such as the exteriors of storage tanks. Stationary equipment is typically located in steel fabrication shops or blast-and-coat shops that perform blast cleaning and coating work. In either case, these machines throw or hurl abrasive at the surfaces to be prepared using high-speed centrifugal (spinning) wheels (Fig. 29b). The abrasive is automatically loaded onto the wheel vanes through a center hub. Stationary machines are multiwheel, whereas portable machines generally have only a single wheel. Recyclable steel abrasives (grit, shot,

Table 2 SSPC-AB 3 abrasive qualification requirements

Qualification test	Industry standard reference
Specific gravity	ASTM C128
Hardness	ASTM E384
Water-soluble contaminants	ASTM D4940
Manganese and phosphorous content	ASTM E350
Cleanliness	Described in SSPC-AB 3 standard
Carbon content	ASTM E1019
Durability	Described in SSPC-AB 3 standard
Particle size distribution	ASTM C136

Table 3 SSPC-AB 4 abrasive qualification requirements

Qualification test	Industry standard reference
Grit requirements	SSPC-AB 1 or AB 3
Dust control	EPA AP-42, section 13.1(a)
Surface profile	Not indicated
Water-soluble contaminants	ASTM D4940
Oil content	ASTM D7393
Health and safety requirements	Not indicated

(a) EPA, Environmental Protection Agency

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Fig. 27 (a) Pliant (sponge) abrasive. (b) Abrasive hopper that accommodates pliant (sponge) media. Photos used with permission from Sponge-Jet, Inc.

Fig. 28 Portable centrifugal abrasive blast machine. Photo used with permission from BlasTrac

or an operating mix of the two) are typically used. The abrasive and debris are collected, the debris is separated, and the abrasive is reloaded and reused. Abrasive breakdown can be monitored by conducting routine sieve analyses (particle size distribution testing in accordance with ASTM C136 using a series of sieves; Fig. 30) or by monitoring the resulting surface profile. If the profile is decreasing, the system will require the addition of fresh abrasive. For specifications requiring an operating mix of steel grit and steel shot, the type, size, and amount of abrasive added to replenish the supply must be monitored. In addition, the operator will typically monitor the abrasive supply in the machine for contamination by oil using the vial test, as described in ASTM D7393 (Fig. 31). All of the grades of blast cleaning can be achieved in theory, but in practice, this method typically produces only the higher grades of cleaning (SSPC-SP 6, SSPC-SP 10, and SSPC-SP 5).

Vacuum blast cleaning (Fig. 32) is similar to dry abrasive blast cleaning, except that the blast nozzle is equipped with a neoprene rubber and bristle brush shroud (collar) that is held tightly against the surface. In this way, the abrasive impacts the surface and is immediately vacuumed off, together with the paint, rust, and mill scale that are dislodged. The debris is separated from the abrasive and the abrasive is reused. Vacuum abrasive blast cleaning is used when a high degree of cleanliness and surface roughness are required but airborne abrasive and dust cannot be tolerated. Surface irregularities can cause the vacuum shroud to lose contact with the surface and result in releases to the environment. Also, vacuum blast cleaning is slow, so it is often limited to preparing small areas. Small pieces or irregular contours on pieces being cleaned may result in vacuum loss, and/or leakage.

Similar to centrifugal wheel blast cleaning, all of the grades of blast cleaning can be achieved in theory, but in practice, this method typically produces only the higher grades of cleaning (SSPC-SP 6, SSPC-SP 10, and SSPC-SP 5).

Wet Abrasive Blast Cleaning. Three variations of this surface-preparation method exist: waterjetting with abrasive induction into the water stream (Fig. 33), abrasive blasting with water induction into the abrasive stream (slurry blast, Fig. 34), and the use of a water collar added to a dry blast nozzle to wet the abrasive (Fig. 35). All three methods employ a mineral or slag abrasive medium. The latter two methods (abrasive blasting with water induction and the use of a water collar) rely on the abrasive to perform the majority of the surface-preparation work. The water is used to wet and suppress the dust and to remove some soluble salt contamination from the surfaces if any is present. In the case of waterjetting with abrasive induction, high-pressure water serves as the removal medium, while the abrasive etches the surfaces and accelerates the cleaning and roughening process.

Any surface-preparation method that incorporates water is going to cause carbon steel surfaces to flash rust. Specifications may require the use of a rust inhibitor (that is compatible with the coating system) to prevent the flash rusting, or simply accept the flash rusting that occurs and select a coating system that is tolerant of it. The SSPC visual guide (discussed later) for wet abrasive blast cleaning illustrates three levels of flash rusting (light, medium, and heavy), so that the degree of tolerable surface rust can be judged by the inspector. Alternatively, a guide was developed for the National Shipbuilding Research Program Surface Preparation and Coatings Panel for evaluating the degree of flash rusting. This is a nonmandatory guide with text and reference photographs describing how to perform a field

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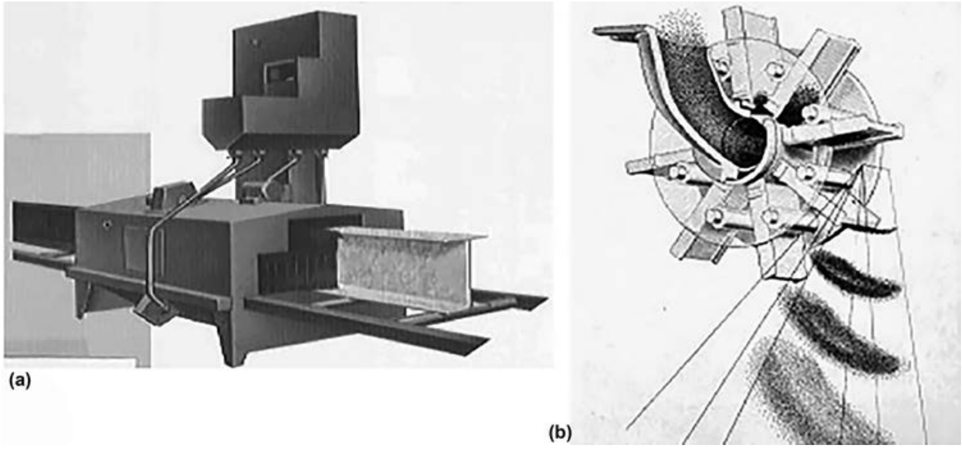

Fig. 29 (a) Stationary centrifugal abrasive blast machine. (b) Diagram of centrifugal wheel propelling abrasive media

assessment of the amount of flash rust on a steel surface by brushing the surface with a paint brush wrapped with a white cotton cloth and evaluating the color and amount of rust that transfers to the cloth.

Wet abrasive also tends to attach itself to the prepared surfaces, which requires thorough rinsing of the surfaces with clean (perhaps rust-inhibited) water to ensure that abrasive debris is not coated over.

When wet abrasive blast cleaning is employed, all of the degrees of blast cleaning can be achieved: SSPC-SP 7, SSPC-SP 14, SSPC-SP 6, SSPC-SP 10, and SSPC-SP 5.

Other nontraditional methods of surface preparation include the use of dry ice, sodium bicarbonate, recycled glass, agricultural abrasives (such as ground corncobs, walnut shells, and peach pits), plastic, and even laser ablation. These methods may be used on soft substrates for which traditional abrasives would be too aggressive. All of these abrasives/removal methods require specialized equipment and generally clean at lower pressures.

Waterjetting. Surface preparation by waterjetting under various water pressures can remove even tightly adhering coating systems from the underlying surfaces but cannot etch an anchor pattern or profile into the surface. However, waterjetting can restore an existing surface profile. The SSPC categorizes waterjetting into four levels:

- Low-pressure water cleaning (up to 35 MPa, or 5000 psi) (Fig. 36)

Fig. 30 Sieves stacked in a series from large openings (top) to small openings (bottom) to monitor abrasive breakdown

Fig. 31 Vial test for abrasive cleanliness

Fig. 32 Vacuum blast cleaning

Fig. 33 Waterjetting with abrasive induction

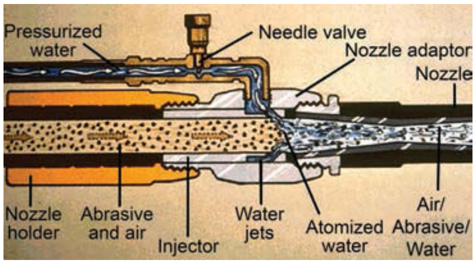

Fig. 34 Diagram of water induction nozzle for wet abrasive blast cleaning

Fig. 35 Water collar/ring

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- High-pressure water cleaning (up to 35 to 70 MPa, or 5,000 to 10,000 psi) (Fig. 37)
- High-pressure water jetting (up to 70 to 200 MPa, or 10,000 to 30,000 psi) (Fig. 38)
- Ultrahigh-pressure water jetting (>200 MPa, or 30,000 psi) (Fig. 39)

Low-pressure water cleaning (LPWC) or pressure washing is often specified for overcoating projects, where the existing coating is salvageable and is incorporated into the maintenance coating system for the structure. Low-pressure water cleaning can be very effective in removing dirt, chalking, bird droppings, and other contaminants from the surfaces, although mechanical agitation of the surface during LPWC is often required to ensure complete removal. A cleaning detergent may also be incorporated into the water. The detergent breaks down the surface tension of the water, allowing it to penetrate and wet better. However, if a detergent is used, it must be flushed completely off the surface prior to coating, because most detergents will interfere with the adhesion of subsequently applied coatings. The remaining three levels of waterjetting are used primarily to remove coatings. As discussed previously, the water employed by these methods causes carbon steel surfaces to flash rust. Specifications may require the use of a rust inhibitor (that is compatible with the coating system) to prevent flash rusting, or one may simply accept the flash rusting that occurs.

The SSPC and NACE International have jointly established separate standards for four degrees of waterjetting. From least to greatest cleaning, they are:

- SSPC-SP WJ-4/NACE WJ-4, “Light Cleaning”
- SSPC-SP WJ-3/NACE WJ-3, “Thorough Cleaning”
- SSPC-SP WJ-2/NACE WJ-2, “Very Thorough Cleaning”
- SSPC-SP WJ-1/NACE WJ-1, “Clean to Bare Substrate”

Chemical Stripping. Removal of coatings using chemical strippers has been widely performed outside of the industrial coatings arena. Methylene-chloride-based paint strippers were used for removing coatings in the residential, commercial, and light industrial markets for years, and the commercial aircraft industry used these strippers to remove coatings from the exterior of the fuselage. However, when chlorinated solvents became recognized as carcinogens (cancer-causing agents), their use as paint strippers declined. Other paint strippers came onto the market and were formulated to work on a variety of surfaces, including wood and steel. These paint strippers were caustic-based (high pH, up to 14) and attacked the resin component of the coating, causing the coating system to disbond from the underlying substrate. Caustic-based paint removers have the consistency of heavy paste and are sprayed or troweled onto the surface. After a few hours of contact time, the stripper is removed from the surfaces (Fig. 40) using scrapers, air or water pressure, or even light blast cleaning. Multiple applications may be required, depending on the coating system type and thickness. Neutralization of the surface after the stripper has been removed is required for proper coating performance.

Environmentally and user-friendly chemical strippers are available that have neutral pH and little odor. They are slower to work on thicker films and may require several applications to remove multiple layers.

Chemical strippers do not generate a surface profile and will not remove rust or mill scale. Therefore, mechanical methods of surface preparation may be required after the coating has been removed. Alternatively, a coating system that is tolerant of intact mill scale and rust can be selected, provided it will perform adequately in the service environment.

No standard is available for chemical strippers, but their use is described in SSPC Technical Update (TU) 6, “Chemical Stripping of Organic Coatings from Steel Structures.” SSPC-TU 6 describes chemical strippers, discusses their use for removing existing conventional organic coatings from steel structures, and acknowledges that chemical stripping is recognized as one of a number of technologies available for the removal of existing coatings prior to repainting. The update describes methods used to identify which type of stripper will work most effectively, typical application and removal options, and containment and disposal options for stripper wastes.

Surface-Cleanliness Standards

The SSPC and NACE International as well as the International Organization for Standardization (ISO) have written and published industry consensus standards for surface cleanliness.

The SSPC and NACE International cleanliness standards are contained in *Systems and Specifications*, Volume 2 of the *SSPC Steel*

Fig. 36 Low-pressure water cleaning

Fig. 37 High-pressure water cleaning

Fig. 38 High-pressure waterjetting

Fig. 39 Ultrahigh-pressure waterjetting

Fig. 40 Sodium-hydroxide-base chemical stripper applied to underside of bridge deck

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Structures Painting Manual. The SSPC and NACE International have jointly published some of the standards, but they are designated by different reference numbers even though the texts are identical. For example, "Near-White Metal Blast" is designated by the SSPC as SSPC-SP 10, while NACE International designates it as NACE 2. There are currently fourteen SSPC surface-cleanliness standards. Seven of the fourteen standards were prepared jointly with NACE International and carry NACE numbers as well. The ISO surface-cleanliness standards are described in ISO 8501-1. There are two hand/power tool cleaning standards (St2 and St3, described earlier), four abrasive blast cleaning standards (Sa1, Sa2, Sa2½, and Sa3), and one flame cleaning standard (F1).

SSPC and NACE International Standards

A brief summary of the requirements of the standards is provided subsequently. Inspection is always performed using the unaided eye or corrected vision. Magnification is not permitted by any of the SSPC surface-cleanliness standards. Four separate visual guides to aid in evaluating the degree of cleanliness are available through the SSPC and NACE International: abrasive blast cleaning, hand and power tool cleaning, waterjetting, and wet abrasive blast cleaning. One pictorial guide is available from ISO. In the event of a dispute, the written standards are the governing documents.

The SSPC surface-cleanliness standards are numbered sequentially in the order in which they are published. For example, SSPC-SP 1 was one of the first surface-cleanliness standards published by the SSPC, and SSPC-SP 16 is the most recent ("SP" indicates surface preparation). Therefore, it cannot be assumed that SSPC-SP 1 represents the lowest degree of cleaning and SSPC-SP 16 represents the highest, or vice versa. Initially, the NACE International designations were sequenced in order of cleanliness (NACE 1 was the highest degree of cleaning, NACE 4 the lowest), but once a decision was made to publish the SSPC and NACE International surface-cleanliness standards jointly, the NACE sequence became obsolete. Note that SSPC-SP 4 and SSPC-SP 9 are discontinued standards and have not been replaced, and that only three of the cleanliness standards (SSPC-SP 11, SSPC-SP 15, and SSPC-SP 16) invoke a specific minimum surface profile (roughness).

SSPC-SP 1, "Solvent Cleaning," requires the removal of all visible grease, oil, lubricants, cutting compounds, and other nonvisible contaminants from the surface. SSPC-SP 1 is a prerequisite to all of the SSPC surface-cleanliness standards (except SSPC-SP 13, "Preparation of Concrete") because mechanical methods of cleaning cannot remove this type of surface contaminant. A surface profile cannot be achieved with solvent cleaning.

SSPC-SP 2, "Hand Tool Cleaning," requires the removal of all loosely adhering rust, mill scale, and paint. The remaining materials are considered tightly adhering if they cannot be lifted using the blade of a dull putty knife. The project specification may require the edges of intact paint to be feathered to facilitate a smooth transition and to prevent lifting of the edge by the application of subsequent coating layers. There is no surface profile requirement for hand tool cleaning.

SSPC-SP 3, "Power Tool Cleaning," is similar to SSPC-SP 2, "Hand Tool Cleaning," in that the standard requires the removal of all loosely adhering rust, mill scale, and paint. The remaining materials are considered tightly-adhering if they cannot be lifted using the blade of a dull putty knife. The project specification may require the edges of intact paint to be feathered to facilitate a smooth transition and to prevent lifting of the edge by the application of subsequent coating layers. There is no surface profile requirement for power tool cleaning.

Note: The SSPC has published three power tool cleaning standards. They vary in the required levels of surface cleanliness and roughness. SSPC-SP 3 is the least aggressive of the power tool cleaning methods and allows all material that is intact to remain.

SSPC-SP 11, "Power Tool Cleaning to Bare Metal," requires the removal of all mill scale, rust, and paint to expose the bare metal surface. If the existing surfaces are pitted, there is an exception to the complete removal of all materials. When pitting is present, trace quantities of paint, rust, and mill scale can remain in the bottom of the pits. The standard also requires that a minimum 25 μm (1 mil) anchor pattern or profile be etched into the bare steel surface.

SSPC-SP 15, "Commercial-Grade Power Tool Cleaning," requires the removal of all mill scale, rust, and paint, except that stains are permitted to remain. Staining from rust, paint, and mill scale is allowed, provided the staining does not exceed 33% (one-third) of each 58 cm^2 (9 $in.^2$) of prepared surface. If the existing surfaces are pitted, trace quantities of paint, rust, and mill scale can remain in the bottom of the pits. SSPC-SP 15 also requires that a minimum 25 μm (1 mil) anchor pattern or profile be etched into the surface.

Abrasive Blast Cleaning Standards for Steel Substrates. The SSPC has published five abrasive blast cleaning standards for steel substrates. They vary in the level of surface cleanliness required. There is no explicit surface profile requirement for any of the abrasive blast cleaning standards. Instead, the standards require that the profile be as required for the coating system. Therefore, the project specification must stipulate the required depth of the surface profile or refer to the coating manufacturer's instructions. The standards, listed in order from least amount of cleaning to greatest, are summarized as follows.

SSPC-SP 7/NACE 4, "Brush-Off Blast Cleaning," requires the removal of all loosely adhering rust, mill scale, and paint by lightly sweeping the surface with the abrasive medium. The remaining materials are considered tightly adhering if they cannot be lifted using the blade of a dull putty knife. The project specification may require the edges of intact paint to be feathered to facilitate a smooth transition and to prevent lifting of the edge by the application of subsequent coating layers. Although there is no surface profile requirement for brush-off blast cleaning, some surface roughening will be created by the abrasive impacting the surface. Brush-off blast cleaning may fracture but not necessarily remove aged, brittle coatings. The risk in this case is that subsequent application of coating to this damaged surface may result in disbonding of the coating film. Use of SSPC-SP 7 to roughen existing surfaces must be done with great care and may not be the optimal choice if the existing coating is old or has become embrittled.

SSPC-SP 14/NACE 8, "Industrial Blast Cleaning," requires the removal of all loosely adhering rust, mill scale, and paint from the surface. Almost all of the tightly adhering materials must also be removed. No more than 10% of each 58 cm^2 (9 $in.^2$) of prepared surface is permitted to contain islands of intact mill scale, rust, or paint. The islands of remaining materials are considered intact if they cannot be lifted using the blade of a dull putty knife. Staining is permitted on any amount of the surface. The project specification may require the edges of intact paint to be feathered to facilitate a smooth transition and to prevent lifting of the edge by the application of subsequent coating layers.

SSPC-SP 6/NACE 3, "Commercial Blast Cleaning," requires the removal of all mill scale, rust, and paint from the surface. Staining from rust, paint, and mill scale is permitted to remain, provided it does not exceed 33% (one-third) of each 58 cm^2 (9 $in.^2$) of prepared surface. The difference between a stain and actual rust paint or mill scale is not defined. Although guides are available, they are visual and can be difficult to use to determine the presence of actual materials left on the surface versus staining. Some experts suggest lightly scratching the surface with a knife. If a powder or flakes are removed, the surface does not meet the SSPC-SP 6/NACE 3 definition, because something more than a stain remains. If the light scraping does not produce a powder or small flakes, the discoloration is considered to be staining and is acceptable as long as it falls within the surface area limit.

SSPC-SP 10/NACE 2, "Near-White Blast Cleaning," requires the removal of all mill scale, rust, and paint from the surface. Staining from rust, paint, and mill scale is permitted, provided it does not exceed 5% of each 58 cm^2 (9 $in.^2$) of prepared surface. See the immediately preceding section for a discussion of staining.

SSPC-SP 5/NACE 1, "White Metal Blast Cleaning," requires the removal of all mill scale, rust, and paint from the surface. Staining from rust, paint, or mill scale is not permitted by the SSPC-SP 5/NACE 1 surface-cleanliness standard.

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SSPC-SP 16, "Brush-Off Blast Cleaning of Coated and Uncoated Galvanized Steel, Stainless Steels, and Non-Ferrous Metals," covers the requirements for brush-off blast cleaning of uncoated or coated metal surfaces other than carbon steel. According to the standard, brush-off blast-cleaned nonferrous metal surfaces, when viewed without magnification, shall be free of all visible oil, grease, dirt, dust, metal oxides (corrosion products), and other foreign matter and uniformly roughened to a minimum surface profile of 19 μm (0.75 mil). Intact, tightly adherent coating is permitted to remain, provided it cannot be lifted with the blade of a dull putty knife. Intact coatings shall be roughened and cleaned as specified in the procurement documents. SSPC-SP 16 also addresses removal of wet storage staining from galvanized surfaces prior to brush blast cleaning and describes a procedure for testing for the presence of passivating treatments (chromating) that can inhibit the adhesion of liquid-applied coating.

Waterjetting Standards. The SSPC and NACE International have jointly established separate standards for four degrees of waterjetting. The four levels of surface cleanliness include the following.

SSPC-SP WJ-1/NACE WJ-1, "Clean to Bare Substrate." Surfaces are free of all visible rust, dirt, previous coatings, mill scale, and foreign matter. Discoloration of the surface may be present.

SSPC-SP WJ-2/NACE WJ-2, "Very Thorough Cleaning." Surfaces are free of all visible oil, grease, dirt, and rust except for randomly dispersed stains of rust, tightly adherent thin coatings, and other tightly adherent foreign matter. The staining or tightly adherent matter is limited to a maximum of 5% of the surface.

SSPC-SP WJ-3/NACE WJ-3, "Thorough Cleaning." Surfaces are free of all visible oil, grease, dirt, and rust except for randomly dispersed stains of rust, tightly adherent thin coatings, and other tightly adherent foreign matter. The staining or tightly adherent matter is limited to a maximum of 33% of the surface.

SSPC-SP WJ-4/NACE WJ-4, "Light Cleaning." Surfaces are free of all visible oil, grease, dirt, dust and loose mill scale, rust, and coating. Any residual material shall be tightly adherent.

The four degrees of flash rusting permitted after waterjetting is completed include:

- None (requires the use of a rust inhibitor)
- Light flash rusting
- Medium flash rusting
- Heavy flash rusting

Other SSPC Surface-Cleanliness Standards. Two standards not otherwise categorized include SSPC-SP 8, "Pickling," and SSPC-SP 13/NACE 6, "Surface Preparation of Concrete."

SSPC-SP 8, "Pickling," prescribes a pretreatment process for steel surfaces prior to hot dip galvanizing. The pickling bath may contain sulfuric or hydrochloric acid and is designed to remove grease, oil, mill scale, rust, and other debris from steel surfaces.

SSPC-SP 13/NACE 6, "Surface Preparation of Concrete," prescribes methods for preparing the surfaces of concrete for coatings and linings and includes mechanical methods (power tools and abrasive blast cleaning), chemical methods (acid etching), and thermal methods (flame cleaning followed by blast cleaning). Information on the degree of roughness, moisture content, and methods to test the adhesion of the applied coating system is also provided in the standard.

International Concrete Repair Institute Guideline 310.2

The International Concrete Repair Institute (ICRI) guideline No. 310.2-1997 (formerly No. 03732), "Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, and Polymer Overlays," addresses methods of surface preparation used on concrete. Although the focus of the guideline is on concrete floors, some of the methods are also suitable for use on vertical and overhead surfaces. The guideline also includes ten concrete surface profile (CSP) coupons that are replicas of the type of profile (surface roughness) created by the various methods of surface preparation. The coupons range in texture from very smooth, typical of acid etching (CSP 1), to extremely rough, typical of hand-held concrete breakers (CSP 10).

Methods addressed in the ICRI guideline are briefly summarized as follows. In addition to the written text, the guideline includes the typical range of surface profiles achieved with each method. Within each category, the methods are ordered from least aggressive to most aggressive.

Methods involving water in ICRI 310.2 include the following:

- *Detergent scrubbing:* Detergents and scrubbing remove surface dirt, oil, grease, and loose debris without altering the texture of the surface. Surface profile: CSP 1
- *Low-pressure water cleaning:* Low-pressure water (<35 MPa, or 5000 psi) removes dirt, dust, loose scale, or debris without removing concrete or texturing the surface. Surface profile: CSP 1
- *Acid etching:* Acids remove weak cement paste and slightly profile the surface by exposing fine aggregate. Acid etching will not remove coatings. Surface profile: CSP 1 to CSP 3
- *High-/ultrahigh-pressure waterjetting:* High-pressure water (from 35 to 310 MPa, or 5,000 to 45,000 psi) removes coatings, the surface of concrete, and water-soluble contaminants. Surface profile: CSP 6 to CSP 9

Methods involving power tools in ICRI 310.2 include the following:

- *Grinding:* Hand-held or floor grinders remove slight surface irregularities and thin coatings. Surface profile: CSP 1 to CSP 3
- *Needle scaling:* Hand-held equipment containing hardened small-diameter steel rods is used to pneumatically impact against the surface to remove coatings and roughen the surface of the concrete. Surface profile: CSP 5 to CSP 8
- *Scarifying:* Hand-held and floor machines containing cutters (toothed washers) impact the surface at a right angle to remove coatings and fracture or pulverize the surface of the concrete. Surface profile: CSP 4 to CSP 9
- *Scabbling:* Hand-held or floor machines containing piston-driven cutting heads impact the surface to remove coatings and the surface of the concrete. Surface profile: CSP 7 to CSP 9
- *Milling/rotomilling:* A machine is driven across the surface to remove the coating and top layer of the concrete through the use of cutting teeth that claw and groove the substrate. Surface profile: CSP 9
- *Hand-held concrete breaker followed by abrasive blasting:* Jackhammers, followed by abrasive blast cleaning, create an extremely rough concrete surface. Surface profile: CSP 10

Methods involving abrasive blast cleaning in ICRI 310.2 include the following:

- *Abrasive (sand) blasting:* Compressed air propels particles of abrasive through specialized hand-held nozzles to remove coatings and roughen the surface of the concrete. Surface profile: CSP 2 to CSP 4
- *Steel shotblasting:* Specialized hand-held or floor machines containing wheels propel a steel abrasive against the surface using centrifugal force. The abrasive is collected by the machine for reuse as the cleaning is being performed. This method removes coatings and roughens the surface of the concrete. Surface profile: CSP 2 to CSP 8
- *Hand-held concrete breaker followed by abrasive blasting:* Jackhammers, followed by abrasive blast cleaning, create an extremely rough concrete surface. Surface profile: CSP 10

Flame blasting in ICRI 310.2 involves the use of an acetylene-oxygen flame to remove paints, contaminants, and contaminated concrete. This is a very dangerous operation. Surface profiles of CSP 8 and higher can be achieved.

Visual Guides and Reference Photographs

There are four visual guides with reference photographs available from the SSPC (Fig. 41). The visual guides are based on the method of surface preparation employed. ISO 8501,

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“Preparation of Steel Substrates before Application of Paints and Related Products—Visual Assessment of Surface Cleanliness, Part 1: Rust Grades and Preparation Grades of Uncoated Steel Substrates and of Steel Substrates after Overall Removal of Previous Coatings,” is used when ISO surface-cleanliness standards are invoked by the specification. The visual guides are not interchangeable between the SSPC and ISO surface-cleanliness standards. The four SSPC visual guides are as follows:

- SSPC-VIS 1, “Guide and Reference Photographs for Steel Surfaces Prepared by Abrasive Blast Cleaning”
- SSPC-VIS 3, “Guide and Reference Photographs for Steel Surfaces Prepared by Power- and Hand-Tool Cleaning”
- SSPC-VIS 4/NACE-VIS 7, “Guide and Reference Photographs for Steel Surfaces Prepared by Waterjetting”
- SSPC-VIS 5/NACE-VIS 9, “Guide and Reference Photographs for Steel Surfaces Prepared by Wet Abrasive Blast Cleaning”

Fig. 41 The SSPC visual guides for surface-cleanliness evaluations

The guides provide reference photographs depicting the appearance of the various grades of cleaning over a variety of painted and unpainted steel substrates. Although they are an excellent supplement to the written requirements of the standards, the photographs rarely match the appearance of actual site-specific conditions. Therefore, it is common for specifications to require the establishment of a project-specific cleanliness standard, generated by preparing a small representative section of the structure to the desired level of cleaning (Fig. 42). The visual guides are used to help establish the degree of cleaning required by the specification. Once established, this area becomes the visual guide for that project. The agreed-upon condition can be preserved by applying a clear sealer to the surface, or digital images can be taken and referenced throughout the project.

International Organization for Standardization

The ISO has prepared two hand/power tool cleaning standards, four abrasive blast cleaning standards, and one flame cleaning standard. The definitions (provided subsequently) are different from the definitions used by the SSPC and NACE International described earlier. The pictorial guides are also different. Any correlation between the ISO surface-preparation standards and the SSPC/NACE International surface-preparation standards is not appropriate. The SSPC “Surface Preparation Commentary” contains two tables identifying the visual guide images for both the SSPC/NACE International standards (based on SSPC-VIS 1 and SSPC-VIS 3) and the pictorial images in ISO 8501-1 (Fig. 43).

ISO St2: “Thorough Hand and Power Tool Cleaning.” “When viewed without magnification, the surface shall be free from visible oil, grease, and dirt and from poorly adhering mill scale, rust, paint coatings, and foreign matter.”

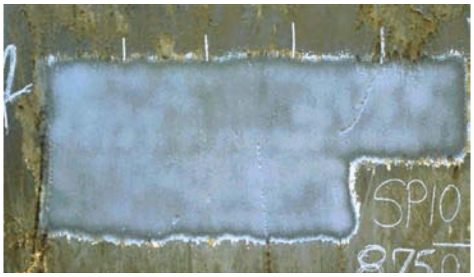

Fig. 42 Project-specific cleanliness standard

Fig. 43 ISO 8501-1 visual guide for surface-cleanliness evaluations

Table 4 Summary of the SSPC and NACE International surface-cleanliness standards

SSPC designation	NACE designation	Title	What must be removed?	What can remain?
SSPC-SP 1	None	“Solvent Cleaning”(a)	Grease and oil contamination	No visible grease and oil
SSPC-SP 2	None	“Hand Tool Cleaning”	Loosely adhering materials	Tightly adhering materials(b)
SSPC-SP 3	None	Power Tool Cleaning”	Loosely adhering materials	Tightly adhering materials(b)
SSPC-SP 5	NACE 1	“White Metal Blast Cleaning”	All mill scale, rust, and paint	Nothing
SSPC-SP 6	NACE 3	“Commercial Blast Cleaning”	All mill scale, rust, and paint	Up to 33% stains(c)
SSPC-SP 7	NACE 4	“Brush-Off Blast Cleaning”	Loosely adhering materials	Tightly adhering materials(b)
SSPC-SP 8	None	“Pickling”	Grease, oil, dirt, mill scale, and rust	Nothing
SSPC-SP 10	NACE 2	“Near-White Blast Cleaning”	All mill scale, rust, and paint	Up to 5% stains(c)
SSPC-SP 11	None	“Power Tool Cleaning to Bare Metal”	All mill scale, rust, and paint	Nothing(d). Must have minimum 25 µm (1 mil) profile
SSPC-SP 13	NACE 6	“Surface Preparation of Concrete”	Not applicable	Not applicable
SSPC-SP 14	NACE 8	“Industrial Blast Cleaning”	Loosely adhering materials	Up to 10% intact rust, paint, or mill scale. Stains on remaining surface permitted(b,c)
SSPC-SP 15	None	“Commercial-Grade Power Tool Cleaning”	All mill scale, rust, and paint	Up to 33% stains(c,d). Must have minimum 25 µm (1 mil) profile
SSPC-SP 16	None	“Brush-Off Blast Cleaning of Coated and Uncoated Galvanized Steel, Stainless Steels, and Non-Ferrous Metals”	Visible oil, grease, dirt, dust, metal oxides (corrosion products), and other foreign matter	Intact, tightly adherent coating(b). Must have minimum 19 µm (0.75 mil) profile
SSPC-SP WJ-1	NACE WJ-1	“Waterjet Cleaning of Metals—Clean to Bare Substrate”	All visible oil, dirt, corrosion, mill scale, coatings, and foreign matter	Discoloration on corroded/pitted steel
SSPC-SP WJ-2	NACE WJ-2	“Waterjet Cleaning of Metals—Very Thorough Cleaning”	All visible oil, dirt, corrosion, mill scale, coatings, and foreign matter except→	Up to 5% stains or tightly adhering matter (e.g., rust, thin coatings)(b,c)
SSPC-SP WJ-3	NACE WJ-3	“Waterjet Cleaning of Metals—Thorough Cleaning”	All visible oil, dirt, corrosion, mill scale, coatings, and foreign matter except→	Up to 33% stains or tightly adhering matter (e.g., rust, thin coatings)(b,c)
SSPC-SP WJ-4	NACE WJ-4	“Waterjet Cleaning of Metals—Light Cleaning”	All visible oil and loosely adhering mill scale, coatings, and foreign matter	Tightly adhering matter(b)

(a) Prerequisite to all methods of surface preparation if deposits are visibly evident. (b) Remaining materials are considered tightly adhering if they cannot be loosened with a dull putty knife. (c) Unit of surface area is approximately 58 cm^2 (9 in.^{2}). (d) Slight residues from paint and rust can remain in the bottom of pits if the original surface is pitted. Source: Ref 1

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ISO St3: "Very Thorough Hand and Power Tool Cleaning." "Same as for St2, but the surface shall be treated much more thoroughly to give a metallic sheen arising from the metallic substrate."

ISO Sa1: "Light Blast Cleaning." "When viewed without magnification, the surface shall be free from visible oil, grease, and dirt and from poorly adhering mill scale, rust, paint coatings, and foreign matter."

ISO Sa2: "Thorough Blast Cleaning." "When viewed without magnification, the surface shall be free from visible oil, grease, and dirt and from most of the mill scale, rust, paint coatings, and foreign matter. Any residual contamination shall be firmly adhering."

ISO Sa2½: "Very Thorough Blast Cleaning." "When viewed without magnification, the surface shall be free from visible oil, grease, and dirt and from mill scale, rust, paint coatings, and foreign matter. Any remaining traces of contamination shall show only as stains in the form of spots or stripes."

ISO Sa3: "Blast Cleaning to Visually Clean Steel." "When viewed without magnification, the surface shall be free from visible oil, grease, and dirt and shall be free from mill scale, rust, paint coatings, and foreign matter. It shall have a uniform metallic color."

ISO F1: "Flame Cleaning." "When viewed without magnification, the surface shall be free from mill scale, rust, paint coatings, and foreign matter. Any remaining residues shall show only as a discoloration of the surface (shades of different colors)."

One should not equate ISO standards with SSPC/NACE International standards; they are different. Table 4 summarizes the SSPC and NACE International surface-cleanliness standards.

Conclusion

As is apparent from the information provided in this article, there are a variety of methods available for removing grease, oil, soluble salts, rust, rust scale, mill scale, and existing coatings from surfaces. There are also variations in the degrees of cleaning and surface roughening that can be achieved by these methods. The degree of cleaning needed for a given application is typically based on the requirements of the coating manufacturer as provided in the coating material product data sheets, but the requirements should be confirmed with the manufacturer based on project-specific needs and service environments. A great deal of additional information on surface preparation is available through the SSPC, NACE International, ASTM International, ISO, and their associated trade journals/publications.

REFERENCE

1. W. Corbett, *Using Coatings Inspection Instruments*, 3rd ed., KTA-Tator, Inc., Pittsburgh, PA, 2012, p 3-3

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ASM Handbook, Volume 5B, *Protective Organic Coatings*
K.B. Tator, editor

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Soluble Salts beneath Coatings

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IT IS WELL KNOWN that soluble salts may potentially degrade a coating on steel by causing osmotic blistering and accelerating corrosion. However, in some environments, salts are not a significant problem, while in others, salts may be very detrimental.

Mechanisms of Coating and Corrosion Degradation by Soluble Salts

Soluble salts on a surface can affect a steel substrate or coating in two principal ways: corrosion acceleration and osmotic blistering. The mechanisms for each of these deleterious effects are discussed as follows.

Corrosion Acceleration. Dissolved salt solutions may accelerate oxidation of steel, resulting in undercutting of a coating system.

Water is one of the most abundant materials on earth. Pure water is considered a universal solvent, dissolving many substances. Rainwater dissolves gases in the atmosphere; entrains particulates in dust, smoke, and other pollutants; and leaches minerals from soils. Most ionic material readily dissociates in water, and water itself will ionize slightly into hydrogen and hydroxide ions. If water-soluble salts are present, they will also dissociate in water, significantly increasing the water conductivity. Corrosion of steel in water increases with increased water conductivity as a consequence of the dissolved materials in water. This conductivity allows the electrical current necessary for electrochemical corrosion to flow between anodic and cathodic areas of the corrosion cell. If the conductivity of the water is low (there are no dissolved ionic solids such as salts), the anodic and cathodic sites on the metal must beadjacent to each other. Negative ions (anions) migrate to and concentrate at the anodic areas of the corroding metal, and positive ions (cations) migrate to and concentrate at the cathodic areas.

In neutral or near-neutral pH water at the anodic areas, metal ions such as Fe^{2+} go into solution. The anodic reaction of steel is:

$$Fe \rightarrow Fe^{2+} + 2e^-$$

At the cathode, hydroxide ions (OH^-) formed by the cathodic reaction with oxygen and water react further with the ferrous ion Fe^{2+} to precipitate an insoluble ferrous hydroxide. Initially formed ferrous corrosion products, with oxygen exposure, convert to hydrated insoluble ferric oxides. The gelatinous nature of these oxides decreases the diffusion rate of reactants and products from the corrosion reaction at the localized cathodes (Ref 1). This slows the corrosion rate, because oxygen cannot diffuse through the gelatinous oxide layer to the cathodic reaction site, and the hydroxide reaction products cannot diffuse away. Thus, the cathodic reaction is said to be the rate-determining reaction in a neutral or near-neutral corrosion process. This cathodic reaction is:

$$2H_2O + O_2 + 4e^- \rightarrow 4OH^-$$

The electrochemical corrosion circuit is completed in the electrolyte (water) by the migration of ions. With increased ion content, the conductivity of water increases, and anodes and cathodes may form at greater distances from each other. There may be more of them, or they can be larger, and ion migration to the anodic and cathodic areas is faster, increasing the rate of corrosion. At the separated anodic and cathodic areas, ions diffuse into solution and do not immediately form insoluble oxide products. Accordingly, there are no insoluble cathodic reaction products and no passive ferrous hydroxide layers forming at the cathode. The electrochemical corrosion reaction continues unabated. The more dissolved salts there are in the water, the greater the corrosion rate. However, with time and oxygen availability, insoluble ferrous oxide products build up, and the corrosion reaction slows.

Also, with increasing salt (sodium chloride) content, the oxygen solubility in water decreases continually. Above 3% NaCl content, the decreased solubility of oxygen becomes more important than any change in the cathodic oxide layer, and hence corrosion decreases.

Thus, dissolved oxygen in the water is the corrosion-rate-determining factor on steel in neutral and near-neutral saltwater environments. In the absence of dissolved oxygen, the corrosion rate of steel is negligible. In oxygen-saturated water, the initial corrosion rate is high but rapidly falls off over a period of days as an iron oxide film is formed that acts as a barrier to oxygen diffusion (Ref 2).

Additionally, water-soluble salts are hygroscopic and, at a critical humidity, will liquefy. The critical relative humidity of a salt is the relative humidity of the surrounding atmosphere (at a given temperature) at which the material begins to absorb moisture from the atmosphere and below which it will not absorb atmospheric moisture.

When a water-soluble salt is in contact with air that has a partial vapor pressure of water greater than that of the saturated brine layer of that salt, additional water will adsorb onto the salt surface. The absorption will continue until the vapor pressure of the saturated salt brine exceeds the partial pressure of the water or until the salt is entirely dissolved. Critical relative humidity (cRH) is defined as the partial pressure of water required for deliquescence (the point at which salt begins to dissolve); for NaCl, this is 75% relative humidity. Water can be desorbed from the brine film as well by the reverse of the aforementioned process. Therefore, if the water content in air is less than 75% relative humidity, NaCl, if damp, will dry out and, if already dry, will remain dry.

While the deliquescence point (i.e., cRH) for pure salts is relatively high, combinations of salts have a lower cRH than the pure components. The cRH for an equimolar NaCl/KCl mixture is 72% at 25 °C (75 °F), while the cRH for NaCl is 75% and for KCl is 82%. Likewise for NaCl containing $MgCl_2$ (cRH not known) or $CaCl_2$ (cRH = 35%), the critical relative humidity will be lowered, the exact value dependent on the amount of $MgCl_2$ or $CaCl_2$ present. The level of sorption or desorption will vary depending on the mixture and the surface area of the particles. The critical relative humidity is much lower for the alkaline earth chlorides (~35% for $CaCl_2$) (Ref 3). The more hygroscopic the salt, the lower is its critical relative humidity. All water-soluble salts and mixtures have characteristic critical humidities; it is a unique material property. Thus, combinations of water-soluble salts may become a problem on a steel surface at humidities much

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lower than the dewpoint, resulting in increased corrosion.

Water-soluble salts on a steel surface, if present, will increase the rate and extent of corrosion. Where such salts are entrapped beneath a coating, and where water can ultimately permeate the coating to dissolve the salt, osmotic blistering and aggressive corrosion of the substrate may occur.

Osmotic Blistering. Osmosis is a physical process in which a solvent moves, without input of energy, across a semipermeable membrane (permeable to the solvent but not the solute) separating two solutions of different concentrations (Ref 3). The solvent of concern with water-soluble salts is water, the semipermeable membrane is a coating or coating system, and the solute is salt ions.

Osmosis may occur when water-soluble salts are entrapped beneath a coating in an immersion or highly moist environment (such as condensing humidity). Water permeates the coating and, with sufficient time, may reach the entrapped soluble salts. The permeating water dissolves the salts, resulting in a highly saturated salt solution entrapped beneath the coating (because the relative concentration of salt dissolved by the initial amount of permeating water is very high). Salt ions do not readily permeate the coating, which acts as a semipermeable membrane and is permeable to water but not to salt ions. The salt concentration outside the coating (on the other side of the semipermeable membrane) is much more dilute, because the water may be quite pure with little or no dissolved salts. Accordingly, there is a strong osmotic driving force across the coating. This driving force results in the net flow of water from the solution of low salt concentration (outside the coating) to the solution of higher salt concentration (entrapped beneath the coating). Water flows through the coating membrane in the direction from the more dilute salt concentration to the higher salt concentration. The flow of water through the coating to the entrapped salt beneath the coating causes distention and blistering of the coating. In most cases, over time the blisters grow to a maximum size, and the osmotic process stabilizes. This time can range from a few days to a few months, depending on the amount and solubility of the entrapped salts, the coating permeability, and the temperature.

Osmosis is a colligative property of the solution, solely dependent on the number (and not the type) of dissolved salt particles, that is, of the molality. For example, 1 mole of water is equivalent to 18.016 g (0.64 oz) of water and contains 1 mole of H_2O molecules but 3 moles of atoms (2 moles H and 1 mole O). Therefore, if soluble salts such as sodium chloride, sodium nitrate, and sodium sulfate are present, their formula weights are approximately 58.5, 85, and 142 g (2, 3, and 5 oz), respectively. However, if those salts dissolve in water and dissociate to form ions, sodium chloride and sodium nitrate each form 2 moles of ions, but sodium sulfate forms 3 moles of ions. Sodium chloride (NaCl) dissociates into 2 moles of ions in water (sodium, Na^+, and chloride, Cl^-); sodium nitrate ($NaNO_3$) into 2 moles (1 Na^+ and 1 NO_3^-); and sodium sulfate (Na_2SO_4) into 3 moles (2 Na^+ and 1 SO_4^{2-}). For sodium chloride, 1 mole of ions is formed for each 29.25 g (1 oz); for sodium nitrate, the mole-ion equivalent is 42.5 g (1.5 oz); and for sodium sulfate, it is 47.3 g (1.67 oz). For these salts, the order of potential for osmotic blistering follows the mole weight but is adjusted for dissociation. Therefore, sodium chloride has the greatest tendency to cause osmotic blistering, followed by sodium nitrate and then sodium sulfate on a mole-weight basis.

However, different soluble salts also have different solubilities in water at a given temperature. For example, the solubility of sodium chloride in 100 g (3.5 oz) of water at 20 °C (70 °F) is 35.9 g (1.27 oz); of sodium nitrate, 87.6 g (3.1 oz); and of sodium sulfate, 19.5 g (0.69 oz). At different temperatures, the solubility of sodium chloride in water remains relatively constant at approximately 36 to 40 g (1.3 to 1.4 oz) for temperatures over the range of 0 to 40 °C (30 to 105 °F), whereas the solubility of sodium nitrate increases from 73 to 102 g (2.6 to 3.6 oz), and that of sodium sulfate increases from 4.9 to 48.8 g (0.17 to 1.7 oz) (Ref 4). (These data come from the 12th edition of *Lange's Handbook of Chemistry*. The 15th edition, Ref 5, gives the solubility of sodium sulfate as 28 g per 100 g of water at 20 °C but no further solubility data at other temperatures.) Figure 1 depicts the solubility of different salts in water at various temperatures.

Accordingly, for these salts, when dissolved, the number of ions in solution is also dependent on their solubility in water at a given temperature. At 20 °C (70 °F), the solubility of sodium nitrate is approximately 2.4 times that of sodium chloride and 4.5 times that of sodium sulfate.

In the blister-formation process, initially the entrapped salt solution is at the saturation point, and the dissolved salt with the highest mole-ion concentration at saturation provides the highest driving force for blistering. At 20 °C (70 °F), sodium nitrate, with a solubility of 87.6 g/100 g (3 oz/3.5 oz) water and a molecular weight of 85 g, dissolves at saturation to an equivalent of 1.03 salt moles or 2.06 ion moles; sodium chloride, with a solubility of 35.9 g (1.27 oz) and a molecular weight of 58.5 g (2.06 oz), dissolves at saturation to an equivalent of 0.61 salt moles or 1.22 ion moles; and sodium sulfate, with a solubility of 19.5 g (0.69 oz) and a molecular weight of 142, dissolves at saturation to an equivalent of 0.14 salt moles or 0.41 ion moles. Initially, at the saturation point of each, sodium nitrate has the highest driving force for osmotic blistering. Once enough water has migrated to the salt to lower the initial salt solution concentration below the saturation point, sodium chloride has the highest osmotic driving force based on the mole-ion equivalent.

The difference in ionic concentration across the coating film also determines the rate and extent of osmotic blistering. If the water outside the coating film is very pure (such as deionized water, with few ions or dissolved salts), there will be more rapid and greater osmotic permeation than if the outside water has a lot of dissolved salts (such as seawater).

Most paint films are almost impermeable to inorganic salt ions (such as Na^+, Cl^-, and SO_4^{2-}), or the film greatly retards salt permeation if it is free from pores and similar defects and is not subject to external electrical potentials such as cathodic protection (Ref 1). Thus, while coating systems are not impermeable to ionic transport, highly cross-linked, intact protective coatings, properly applied and cured, are highly resistant to ionic transport; for these coatings, salts causing osmotic blistering usually must be deposited onto the surface beneath the coating.

Later research leads to the conclusion that the rate of delamination of coatings in the presence of applied cathodic potentials was determined by the rate of ionic migration through a coating. The ion-transport process may occur in the absence or presence of an externally applied potential. It was apparent that a coating is permeable to ions and that the type of ions present in the electrolyte controls the ability of the coating to transport charge. Ion transport under many conditions occurred largely by way of continuous pathways through a polymer coating. The dimensions of these pathways and their geometry within the coating are unknown, although it is suspected that they have diameters before immersion in the electrolyte on the order of 1 to 10 nm (Ref 7).

Once the corrosion process starts, local changes in the pH or in the ion concentration within the pathway lead to degradation of the coating and either an increase in the diameter of the pathway or an improvement in its continuity. A coating that retains solvent may also affect the pathways by introducing stresses in the coating and leaving voids through which ion transport may occur.

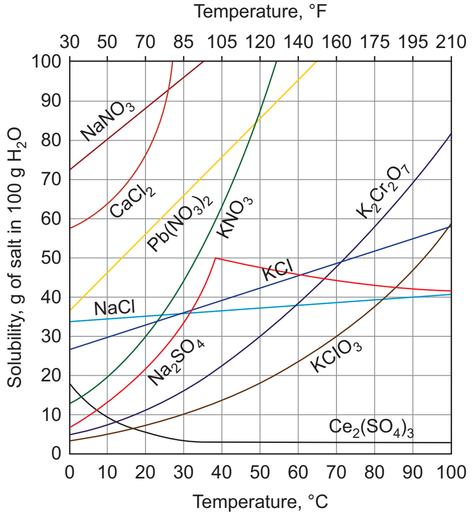

Fig. 1 Solubility of common inorganic compounds in grams solute per 100 g of solvent. Source: Ref 6

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