The inadvertent transfer of thermal energy in the form of heat leads to a variety of issues in industrial settings. Issues include heat loss from processing equipment and piping, increased energy usage, worker injuries from contact with hot substrates, and associated costs. The traditional insulation methods to combat these issues include use of materials such as fiberglass and polyurethane foam; however, thick layers of insulation can often hide severe maintenance problems such as corrosion under insulation (CUI).

An alternative to traditional insulation is the use of thin-film thermal insulation coatings based on waterborne acrylic and epoxy resins. This article describes our efforts to better understand the polymer design and formulation parameters for these thin-film waterborne thermal insulation coatings. Their potential use in thermal insulation will be described through test results on thermal conductivity, safe-touch properties, and corrosion performance in multi-layer systems that can be applied by traditional methods. Both one-component waterborne acrylic and two-component waterborne epoxy resins and coating formulations have been evaluated and compared to commercial insulation coatings. The use of two types of low thermal conductivity fillers, hollow glass microspheres and silica aerogel, is also described.

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Developments in Waterborne Thermal Insulation Coatings

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How Heat Transfers

Heat transfers between materials by one or more of three main processes: conduction, convection, and radiation. Heat moves through a solid by conduction, and the rate of the conduction depends on the chemical nature and structure of the solid. Some solids, like extruded polystyrene foam, are designed to inhibit conduction, while others, like copper, are highly conductive and allow heat to pass freely. Convection is the transfer of heat by the movement of a fluid, such as a liquid or gas. Heat can also be emitted by an object through radiation in the form of electromagnetic waves such as infrared light. Radiation of heat leads to the familiar warming sensation experienced when we near a fire or hot wood stove.

Thermal conductivity (k) is the rate at which heat flows through a material between points at different temperatures, and is measured in units of watts per meter per degree Kelvin (W/mK). Heat flux (Q), or the rate at which heat energy is transferred through a given surface (units of W/m^2), is most often determined by measuring a temperature difference over a piece of material with known thermal conductivity. For a material to exhibit thermal insulative properties, it must have very low thermal conductivity. Table 1 gives thermal conductivity values at room temperature of some common materials.

Types of Thermal Insulation for Industrial Plants

Thermal insulation found in most industrial plant operations is used on reaction vessels, pipelines (e.g., steam or chilled water), transfer pipes, heat exchangers, storage tanks, and other equipment. Traditional materials in these settings include calcium silicate,[1] expanded perlite,[2] cellular glass,[3] organic foams (e.g., polyurethane, polyisocyanurate, elastomeric, phenolic, polystyrene),[4] and man-made mineral fibers (e.g., fiberglass).[4]

To maintain its effectiveness and to prevent corrosion issues, insulation typically requires a separate moisture barrier or jacketing to keep out water. Insulated surfaces for carbon steel operating above 149 C (300 F) and below -4 C (25 F) are generally thought to not present major corrosion issues. However, for equipment operating between these temperatures, significant corrosion can occur underneath the insulation. The traditional insulation materials create a significant barrier to inspecting the steel surface. CUI can result in equipment failures, production losses, and increased costs.[5] Corrosion occurs when moisture comes into contact with steel surfaces underneath the insulation. CUI can go undetected because the damage is not visible until the insulation is removed.

Opposite page: Photo courtesy of the Dow Chemical Company

Table 1: Thermal Conductivity of Common Materials

Material	Thermal conductivity, k (W/ mK)
Air	0.02
Aluminum	237
Calcium silicate	0.05
Carbon steel (max 0.5% C)	54
Concrete (lightweight)	0.1–0.3
Copper	385
Expanded polystyrene foam	0.03
Glass (borosilicate glass)	1.14
Hollow glass spheres	0.030
Polyurethane foam	0.03
Rock wool	0.04
Silica aerogel	0.004–0.03
Stainless steel (austenitic, type 304)	15
Water	0.6
Wood (Eastern white pine, oven dry)	0.09

The maintenance costs resulting from CUI have led to enhanced interest in better coating and insulating material systems and the development of functional, liquid-applied thermal insulation coatings. Replacing thick jackets of insulation with a relatively thin, liquid-applied coating with thermal insulation properties has several advantages, including greater ease of application, through traditional methods; application to surfaces with complex geometries; and prevention of CUI through easier inspection for corrosion of metal surfaces. The insulation coating becomes part of the overall coating system, and it can be used with primers and topcoats to provide a system with good durability and corrosion resistance.

Thermal insulation coatings also must protect workers against burns from contact with very hot surfaces. Human skin is very sensitive to temperature within a narrow range. Burn injuries depend on three primary factors: 1) surface temperature of the object being touched, 2) thermal conductivity of the surface, and 3) contact time with the surface. Metals such as steel or aluminum have much higher thermal conductivities than other construction materials, such as wood or concrete (Table 1). The higher thermal conductivity translates into more thermal energy being transferred from the substrate to the skin. Thermal insulation coatings with low thermal conductivities can therefore help protect workers by lowering the surface temperature and slowing down the transfer of thermal energy from the surface to human skin.[6-7]

The current dominant insulation technology is one-component waterborne acrylics coatings, formulated with low thermal conductivity fillers such as hollow glass or ceramic microspheres, and, more recently, with silica aerogels.[8] The hollow glass microspheres are made from sodium or aluminum borosilicate glass with a small amount of air trapped in the micron-sized void space. The trapped air is "still," which contributes to the low thermal conductivity. The silica aerogel particles are extremely porous, hydrophobically treated silica with an open pore structure. The highly hydrophobic nature of the particles keeps water out of the pore space of silica aerogel. Aerogel silica provides low thermal conductivity because of the "still" air in the very small pores (approximately 20 nm diameter) and very low density.

The liquid-applied insulation coatings are therefore composite materials made of functional fillers bound together with a polymer that provides cohesive strength, adhesion to the substrate, flexibility, and stability to constant high service temperatures. Commercial acrylic-based insulation coatings are recommended for use up to approximately 204 C (400 F). With high pigment volume concentrations (PVC) and low polymer glass transition temperatures (T_g), these coatings can be formulated at low VOC levels and high solids. They can be applied directly to the substrate or over a corrosion-inhibiting primer and then topcoated. The primers provide the corrosion protection in a multi-coat system, and the topcoat provides decorative properties and protection to the insulation coating.

Our efforts to understand and further develop formulation knowledge of thin-film, liquid-applied thermal insulation coatings are described in the remainder of this article.

Experimental

We carried out initial experiments using design of experiments (DOE) methodology to quickly screen and narrow the choice of potential polymer and filler candidates for a low thermal conductivity insulation coating. From these experiments, two waterborne acrylic-styrene latex polymers (EXP-A and EXP-B) and one water-

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borne epoxy resin dispersion (EXP-C) were chosen for further formulation development because of their ability to be formulated at low VOC and high volume solids, and to provide coatings with low thermal conductivity and good corrosion protection. Both acrylics have a hydrophobic backbone, and offer excellent water resistance properties. EXP-A has a T_g of 19 C and EXP-B has a slightly lower T_g of 13 C. The waterborne epoxy dispersion EXP-C is a dispersion of a Type 1 solid epoxy, with a minimum film formation temperature of 13 C and an epoxy equivalent weight of 1050. It was cured with a waterborne polyamine adduct with 50% weight solids and an amine hydrogen equivalent weight of 300.

The three resins were formulated into insulation coatings using the two fillers chosen from the DOE experiments for their ability to give low thermal conductivity values and good coating processing. Commercially available, the fillers included a hollow glass microsphere (GL) and a silica aerogel (AER). Coatings were prepared according to the design in Table 2. The fillers were used as the sole filler as well as in

Table 2: Coating Identification for Insulation Coatings Evaluated

Polymer Filler	EXP-A WB acrylic	EXP-B WB acrylic	EXP-C WB epoxy
GL @ 75% PVC (hollow glass spheres)	A-1	B-1	C-1
GL @ 50% PVC / AER @ 25% PVC	A-2	B-2	not tested
GL @ 25% PVC / AER @ 50% PVC	A-3	B-3	not tested
AER @ 75% PVC (silica aerogel)	A-4	B-4	not tested

combinations. Formulations based on the epoxy resin EXP-C and containing silica aerogel filler (AER) did not have good processing, with high viscosities or gelling, and were not evaluated further.

The insulation coatings, prepared using a conventional paint making process, are very high-solids (approximately 70% volume solids), low VOC waterborne coatings. Examples of model formulations are provided in the original

paper given at SSPC 2013 (sspc.org).

Experimental insulation coatings based on EXP-A, EXP-B and EXP-C were compared with two commercially available insulation coatings, COM-1 and COM-2. Both of the commercial coatings are reportedly based on waterborne acrylic technology, although the supplier technical literature does not reference specific filler technology.

Coatings were tested for thermal conductivity according to ASTM C518, which describes the method for determining thermal conductivity of a flat specimen at a steady state condition using a flow meter.[9] The thermal conductivity of an uncoated polycarbonate sheet of known thickness is measured. The insulation coatings were applied to the 8-inch x 8-inch clear polycarbonate panels at a dry film thickness (DFT) of approximately 80 mils (2 mm) and cured for seven days at room temperature. The thermal conductivity is determined by measuring the sample thickness, heat flux, and temperature difference across the two plates within the flow meter (Fig. 1). Using the known values of thermal conductivity and thickness for the polycarbonate, the temperatures of the bottom and top plates, the thickness of the coating, and the measured value of heat flux (Q) for the system tested, the thermal conductivity of the coating can be calculated using Fourier's Law of Heat Conduction.

Free films of the coatings at 40 mils' DFT were cast on release paper and tested for tensile and elongation according to ASTM D638. Adhesion was tested according to ASTM D3359 for coatings applied to clean, smooth cold-rolled steel at 25 mils' DFT.

Humidity resistance was evaluated by casting films on clean, smooth cold-rolled steel at 50 mils' DFT, drying for a week at room tempera-
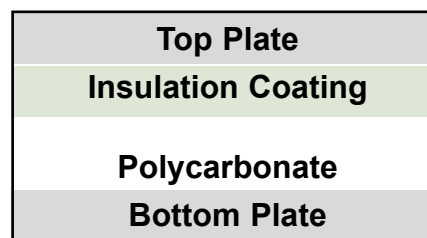

| Top Plate |
| Insulation Coating |
| Polycarbonate |
| Bottom Plate |

Fig. 1: Schematic diagram of heat flow meter configuration for thermal conductivity testing Figures courtesy of the authors

ture, and placing the panel in a Cleveland condensation cabinet, according to ASTM D4585. Films were evaluated for blistering and rusting at various exposure times.

Corrosion resistance of systems, including the insulation coatings as a topcoat over an anti-corrosive primer, was tested according to ASTM B117. The primer was an experimental two-component waterborne epoxy formulated with inhibitive pigment. The primer was applied at 3 mils' DFT on smooth cold-rolled steel and cured for seven days at room temperature, then topcoated with 50 mils' DFT of insulation coating and dried for another seven days. Panels were scribed before exposure and rated for blistering and rusting.

The ability of the insulation coating to reduce the surface temperature of hot steel was determined by placing a coated piece of steel on a hot plate and measuring the surface temperature of both uncoated and coated steel with a handheld infrared thermometer. A piece of smooth cold-rolled steel was coated with 75 mils' DFT of the insulation coating and allowed to dry for seven days before testing. Panels were placed directly on a hot plate set to 180 F and allowed to equilibrate. Surface temperature was measured every 10 minutes until it reached an equilibrium value. A side-by-side comparison with an uncoated piece of steel was done in every instance.

Results and Discussion

Table 3 shows the results of thermal conductivity measurements for the various combinations of binder and filler. The main contribution for the low thermal conductivity values is from the functional fillers, which, for the experimental formulations, are either the hollow glass microspheres

Table 3: Results of Thermal Conductivity Measurements

Coating	Polymer	Polymer Type	Hollow glass microsphere (%PVC)	Silica aerogel (%PVC)	Thermal conductivity, k (W/mK)	Thermal conductivity, k (mW/mK)
Uncoated polycarbonate	N/A	N/A	N/A	N/A	0.1649	164.9
COM-1	unknown	acrylic	-	-	0.070	70
COM-2	unknown	acrylic	-	-	0.106	106
A-1	EXP-A	acrylic	75	0	0.080	80
A-2	EXP-A	acrylic	50	25	0.080	80
A-3	EXP-A	acrylic	25	50	0.130	130
A-4	EXP-A	acrylic	0	75	0.120	120
B-1	EXP-B	acrylic	75	0	0.0850	85
B-2	EXP-B	acrylic	50	25	0.0880	88
B-3	EXP-B	acrylic	25	50	0.127	127
B-4	EXP-B	acrylic	0	75	0.104	104
C-1	EXP-C	epoxy	75	0	0.107	107

(GL) or the silica aerogel (AER). The exact type of filler used in the commercial coatings is unknown. The experimental formulations display values from 0.08 to 0.13 W/mK, which are similar to those observed for the commercial coatings COM-1 and COM-2 at 0.07 and 0.11 W/mK, respectively.

Although a low thermal conductivity was achieved with all the experimental formulations, there are differences among formulations containing the same polymer but different filler combinations, even though the PVC is held constant at 75%. For example, in the formulations with acrylic EXP-A, the coating with only hollow glass microspheres (A-1) has the lowest thermal conductivity, while the coating with only silica aerogel (A-4) has the highest. This result is somewhat surprising because the silica aerogel is a lower density material and should lead to a lower density coating, presumably containing a higher level of still air. The lower density in the wet state is confirmed by measurements of wet density that closely match the calculated values. Although we have not yet confirmed the reason through experiments, we postulate that the difference may be due to the density of the dry film, and we suspect that some polymer intrusion into the open cell pore structure of the silica aerogel may be occurring and displacing air.

The ability of the insulation coatings to provide safe-touch properties was evaluated by measuring the decrease in surface temperature of coated steel compared to uncoated steel. At the film thickness tested, all of the coatings gave a significant decrease in surface temperature (Fig. 2). Most of the coatings gave a surface temperature of 140 F (60 C) or below, which is needed to pass the five-second contact that would result in a first-degree burn.[6-7]

Some differences were noted among the experimental insulation coatings based on filler type, and correlate with the thermal conductivities discussed above. Hollow glass microspheres were more efficient at lowering the surface temperature than the silica aerogel at the same PVC. For example, in coatings made with acrylic polymer EXP-A, coatings A-1 (75% PVC hollow glass microspheres) and A-2 (50% PVC glass microspheres/25% PVC silica aerogel) had surface temperatures of 140 F and 138 F, respectively, compared to coatings A-3 (25% PVC glass spheres/50% silica aerogel) and A-4 (75% PVC silica aerogel) with surface temperatures of 146 F and 148 F. The ability to provide safe-touch properties depends not only on the thermal conductivity and heat flux properties of the coating, but also on the service temperature of the metal surface and film thickness of the coating. At higher metal temperatures, thicker films will be needed to bring surface temperatures down to the required levels for safe-touch protection.

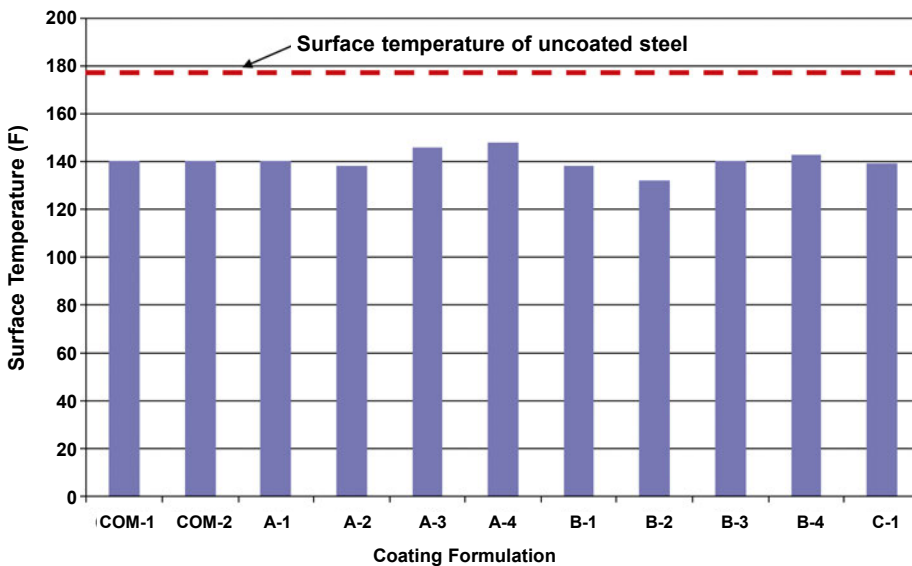The insulating properties of the coatings are

Fig. 2: Surface temperature of insulation coatings at 75 mils' DFT on steel heated to 180 F

Table 4: Results of Tensile, Elongation, Adhesion, Humidity, and Salt Spray Testing for Insulation Coatings

Coating	Tensile strength (psi)	Elongation at break (%)	Adhesion	1,000-hr Humidity exposure	2,016-hr Salt spray exposure blisters
COM-1	brittle	brittle	5B	no blisters or rust	none
COM-2	169	30	5B	no blisters or rust	none
A-1	185	61	5B	no blisters or rust	none
A-2	196	103	5B	no blisters or rust	none
A-3	204	156	5B	no blisters or rust	none
A-4	173	243	5B	no blisters or rust	none
B-1	113	73	5B	no blisters or rust	none
B-2	137	93	5B		
B-3	182	325	5B	no blisters or rust	none
B-4	182	300	5B	no blisters or rust	none
C-1	brittle	brittle	5B	no blisters or rust	none

largely due to the low thermal conductivity of the functional fillers. The polymer in the insulation coating also contributes to important properties such as adhesion to the substrate, flexibility, and barrier properties (water and corrosion resistance). In some ways, the role of the binder in the highly filled insulation coatings is similar to the role of the binder in highly filled organic zinc-rich primers. The main role is to hold the functional filler particles together in a cohesive film that will adhere to the substrate and withstand the stresses imposed on the coating (e.g., impact, flexing, UV light and water). Table 4 shows results of tensile and elongation measurements, adhesion testing, and barrier properties. Adhesion was measured on a smooth steel substrate, and all of the experimental and commercial coatings performed well, with no failure in crosshatch tape adhesion testing. Elongation measurements on free films demonstrate that all of the experimental acrylic-based coatings performed much better than the commercially available coatings and the epoxy-based coating C-1. COM-1 and C-1were too brittle to prepare a free film to get an accurate measurement, and COM-2 had only 30% elongation. Compared to COM-2, the experimental acrylic coatings had from two to ten times the percent elongation, ranging from 61 to 325% elongation. The type of filler significantly affected percent elongation. In general, higher levels of silica aerogel provided higher percent elongation. The correlation between silica aerogel level and percent elongation is strong for the acrylic-based coatings, and represents a key reason to include this filler in insulation coating formulations. Higher elongation typically translates into improved flexibility, which suggests that coatings containing some silica aerogel will be less prone to cracking when placed under stress. We are currently examining this hypothesis through thermal cycling, impact and flexibility, and exterior exposure testing.

Barrier properties for the coatings were examined through humidity (Cleveland condensation cabinet) and salt spray exposure testing (Table 4 and Fig. 3). The coatings were applied directly to smooth cold-rolled steel for humidity testing, and performed very well after 1,000 hours' exposure to condensation, with no blistering or rusting. Salt spray testing was performed over smooth cold-rolled steel panels that were first

Salt spray results—2,016 hours

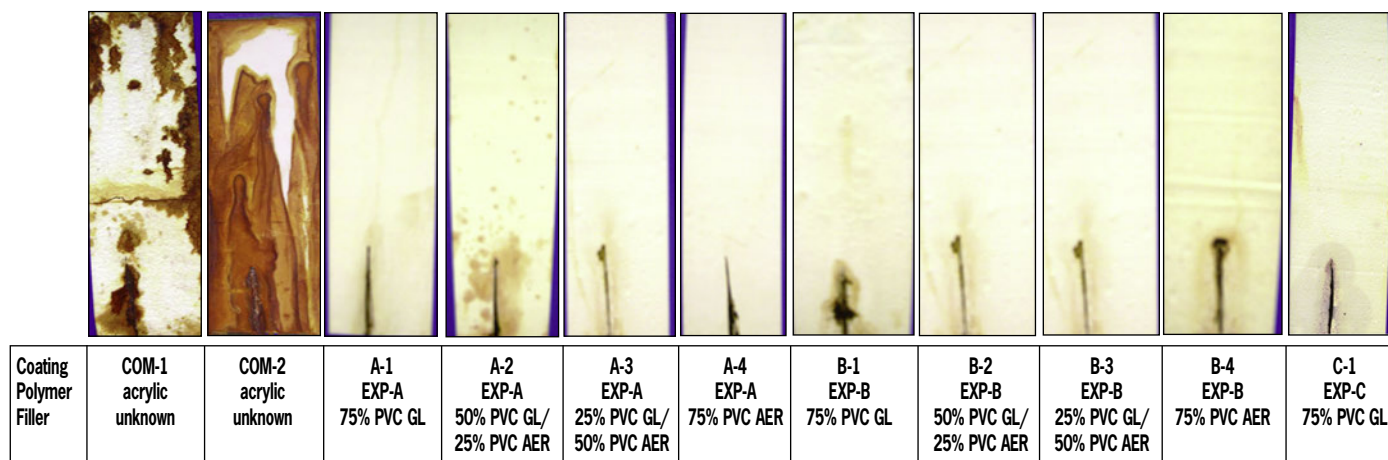| Coating Polymer Filler | COM-1 acrylic unknown | COM-2 acrylic unknown | A-1 EXP-A 75% PVC GL | A-2 EXP-A 50% PVC GL/ 25% PVC AER | A-3 EXP-A 25% PVC GL/ 50% PVC AER | A-4 EXP-A 75% PVC AER | B-1 EXP-B 75% PVC GL | B-2 EXP-B 50% PVC GL/ 25% PVC AER | B-3 EXP-B 25% PVC GL/ 50% PVC AER | B-4 EXP-B 75% PVC AER | C-1 EXP-C 75% PVC GL |

Fig. 3: Panels coated with insulation coatings, after 2,016 hours of salt spray exposure. Panels were primed with a waterborne epoxy.

primed with 3 mils' DFT of an experimental waterborne epoxy primer and topcoated with 50 mils' DFT of the insulation coatings. Pictures of several salt spray panels after 2,016 hours' exposure are shown in Fig 3. Both commercial coatings performed poorly as part of the coating system, with heavy rusting bleeding through the insulation coatings COM-1 and COM-2. The formulation parameters for the commercial coatings are unknown, but film porosity and water permeability may be higher than the experimental coatings due to choice of polymer and filler type and levels. In general, the experimental coatings performed well in a system over the waterborne epoxy primer, with no blistering and little rust bleed. Only coating A-2 showed appreciable rust spots bleeding through the insulation coating. Additional testing over waterborne acrylic primers showed similar performance, although the systems primed with the waterborne epoxy did slightly better in blister resistance. Although their main function is to provide insulation properties, insulation coatings can add to the corrosion resistance of a coating system due to their barrier properties. The use of hydrophobic acrylic polymers and highly cross-linked waterborne epoxy resins with the proper choice of fillers yields a thick-film coating that helps resist corrosion by preventing water and electrolyte from reaching the steel surface.

Conclusions

Entrapped air between the fibers or cell structure of traditional insulation leads to very low thermal conductivity for those materials. A class of functional fillers, including hollow glass microspheres and silica aerogel, are available for use in coatings and building products, and derive their low thermal conductivity from the presence of air trapped in their small voids and pores. When incorporated into waterborne coatings based on acrylic or epoxy polymers, the functional fillers lead to a new class of insulating materials: waterborne thermal insulation coatings. These insulation coatings offer a number of advantages compared to traditional insulation, including easy spray application, less risk of CUI and easier inspection, simple application to complex geometries, improved personal protection (i.e., safe-touch) properties, and energy savings through their insulating properties.

Excellent elongation properties have been observed with the acrylic insulation coatings, particularly when silica aerogel is included as part of the functional filler. Higher elongation compared to commercially available coatings should translate to better flexibility in situations where it is needed. Finally, the ability of the insulation coating to perform its functional purpose, i.e., insulation, is important, but we have also shown that it can take part in the protective qualities of the coating system. We have demonstrated that a waterborne system consisting of a waterborne epoxy primer topcoated with a waterborne insulation coating can offer good corrosion resistance properties on steel. For the experimental insulation coatings described in this work, the acrylic and epoxy resins and functional fillers such as silica aerogel are hydrophobic by design, and, with proper formulation, offer a good barrier to water and electrolytes and thus improve the corrosion resistance of the overall system.

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