Corrosion under insulation

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17.1 Introduction

Corrosion under insulation (CUI) is one of the costliest problems facing the oil and gas industry today. According to many corrosion engineers, problems such as major equipment stoppages unexpected maintenance costs stemming from CUI result in more unplanned downtime than all other causes. In the 1950s there were reports of incidences of CUI, but it was not until the 1980s that there was an increased effort to mitigate CUI. Today it is a widespread problem in the oil and gas industry counting for as much as 80% of all pipe maintenance costs. As an example a study carried out between 1999 and 2001 detailed the direct cost of corrosion in the United States was estimated to be $276 billion dollars a year, i.e., about 3% of the gross domestic product. $121 billion dollars was spent on preventing corrosion, and 88.3% was spent on organic coatings. How many of these figures were exclusively related to upstream and transmission sectors was not quantified but is expected to be substantial. The use of coatings under insulation as part of a thermal insulation system has been shown to be a good solution to mitigate CUI. A very aggressive corrosive environment can occur under the insulation, but the installed insulation will hide the onset of corrosion, and the damage might not be discovered until serious event occurs, potentially causing injury or even a fatality. Because inspection or nondestructive onstream examination is difficult and almost as costly as in situ repainting of the pipes in the field, very high demands are set for the coatings.

In oil and gas production, areas such as steel piping, storage tanks, container vessels, and other *process* equipment are all subject to a variety of temperature fluctuations. Thermal insulation installed onto the pipe or vessel mitigates these effects. However, the occurrence of seams and gaps, inadequate system design or incorrect installation, damages resulting from poor maintenance practices, or other discontinuities in the insulation system makes them susceptible to ingress of water and contaminants. Sources of water can include rainfall, cooling tower drift, steam discharge, wash downs, and, because insulation is not vapor tight, condensation. Once wet, the insulation system's weather barriers and sealants trap the water inside, so the insulation remains moist for extended periods of time creating a very aggressive corrosive environment.

Typical types of insulation may be calcium silicate, expanded perlite, man-made mineral fibers, cellular glass, organic foams, or ceramic fiber. Depending on the type of insulation employed, this will vary in its water retention, permeability, and wettability characteristics. The real issue is that the insulation and cladding hides

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the protective coating system that is protecting the steel substrate. Inspection ports, which provide less than 1% visibility to the metal surface, are not likely to be representative of the whole asset. Removal of insulation is usually a last resort because of cost and is typically performed only on a 15–20 year cycle. Therefore with no full removal of the thermal insulation for metal surface inspection, over time the coating system that was intended to protect the asset against corrosion can prematurely fail. It is therefore often likely for a maintenance engineer to come along, and during removal of insulation, to complete a minor repair job and likely to unearth a degree of corrosion that represents a bigger problem.

CUI not only affects carbon steel (CS) but also has a damaging effect on austenitic and duplex stainless steel (SS) substrates. In CS, CUI occurs in piping or equipment with a skin temperature in the range of −4 to 150°C (25–302°F) [1], where the metal is exposed to moisture over a period of time under any kind of insulation. The rate of corrosion varies with the specific contaminants in the moisture and the temperature of the steel surface. Waterborne chlorides and sulfates concentrate on the CS surface as the water evaporates.

In austenitic and duplex SSs, a phenomenon called external stress corrosion cracking (ESCC) occurs, but the temperature threshold is higher—between 50 and 150°C (120–302°F) [1]. For ESCC to develop, sufficient tensile stress (residual or applied) must be present. Here again, waterborne chlorides concentrate on the SS hot surfaces as water evaporates.

17.2 Examples of CUI failures

The first case [2] was a failure of an ethylene vapor line as shown in Fig. 17.1(a)–(c). The original engineering specifications of the plant reported that the line was operating at −24°C (−12°F). During inspection surveys, this was considered as high risk. However, after investigation, it became apparent that this operating temperature was only

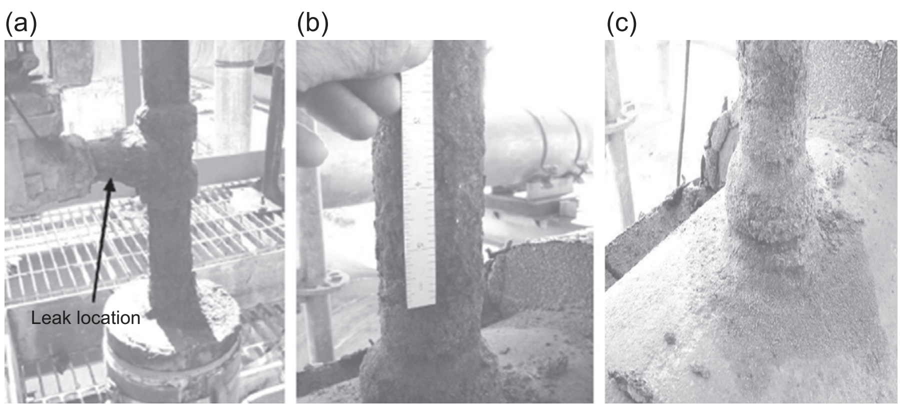

Figure 17.1 (a) Location of the leak, (b) corrosion of the vent line at 14″ branch connection, (c) corrosion of the vent line at 14″ branch connection.

correct when the pressure control valve was open and flowing. The normal operation of the valve was to be in the closed position, creating a stagnant leg with no flow. Therefore in reality the typical temperature of the line was only slightly below ambient. On removing the insulation at the location of the leak, it was found that the corrosion extended beyond the area of the leak and traveled further down the pipe back to a 14-inch line. On further inspection and removal of insulation the CUI issues were found to be more prevalent.

The second example (Fig. 17.2) was a storage tank that contained hot asphalt. During a heavy storm, its cladding and insulation were blown away, revealing extensive corrosion that had not been anticipated because no external evidence had been observed. There were areas of very significant metal loss after only 14 years—likely requiring a total replacement of the tank.

The third example is shown in Fig. 17.3 illustrating a pipe coated with inorganic zinc (IOZ)−rich primer that had been under insulation running at less than 93°C (200°F). The worst part of the corrosion was found in temperatures between 71 and 82°C (160−180°F). The key issue in this case was the incorrect specification of IOZ silicate for use in this temperature range under insulation.

The images in Fig. 17.4 show other typical examples that have been seen in oil and gas facilities during inspections. In all cases the corrosion was found at a late stage and had progressed to a point that in one case resulted in shut down and replacement of the steel.

17.3 Current understanding and industry knowledge

17.3.1 Mechanism of corrosion under insulation

CUI of CS is essentially an electrochemical reaction that consists of an oxidation reaction and a reduction reaction. Most metals and alloys prefer the ionic state rather

Figure 17.2 Corrosion under insulation on Naptha tank.

Figure 17.3 Corrosion under insulation on inorganic zinc pipe section.

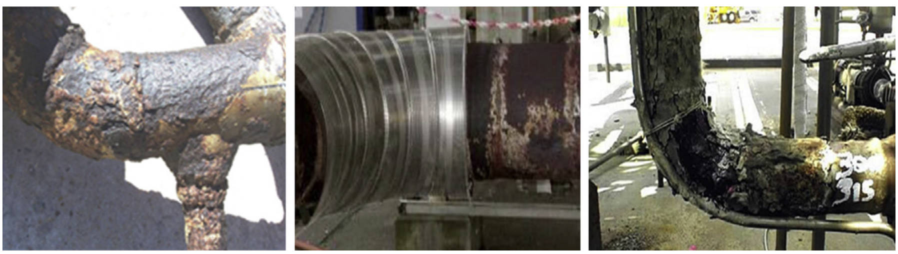

Figure 17.4 Further examples of corrosion under insulation. These photos are very typical of what is found on daily basis.

than remain in an elemental state. An oxidation reaction is where the metal atoms give up electrons and enter an ionic state. The site at which an oxidation reaction occurs is the anode. The two common iron oxidation reactions are

$$Fe = Fe^{2+} + 2e^- \quad \text{and} \quad Fe = Fe^{3+} + 3e^-$$

The electrons are then transferred and become part of another chemical species as part of a reduction reaction. When the steel surface is in contact with water containing dissolved oxygen and the presence of the free electrons, this results in the reduction reaction:

$$O_2 + H_2O + 4e^- = 4OH^-$$

The site at which the reduction reaction occurs is the cathode. The OH^- anions react with the Fe^{2+} and Fe^{3+} to form $Fe(OH)_2$ and $Fe(OH)_3$, respectively. The final reaction is the reformation of the H_2O and the precipitation of the Fe_2O_3 oxide. The total chemical reaction is

$$4Fe + 6H_2O + 3O_2 = 4Fe(OH)_3 = 6H_2O + 2Fe_2O_3 \text{ (precipitation)}$$

CS that is insulated corrodes because of being in contact with aerated water. The role of insulation provides a crevice that retains the water and corrosive media, the material may wick (i.e., absorbs or transports moisture via capillary action) and absorb water, and the material may contribute contaminants that increase or accelerate the corrosion rate. The primary water sources are infiltration from external sources and condensation. Contaminants in water can increase the conductivity of the water environment.

It's a common knowledge among experienced corrosion engineers dealing with CUI that dry insulation systems simply do not exist, and there is no such thing as 100% waterproof insulation throughout the life of the installed insulation. It is also a myth that at elevated service temperatures, that moisture could never get trapped within the insulation system. This leads to the fact that in many piping systems, no coating other than a basic inorganic shop primer was ever applied. The truth is that the primary function of jacketing is weatherproofing and not vapor barrier. Depending on service temperature and ambient conditions, condensation within the insulation system may not be avoidable and therefore needs to be addressed in the design/engineering phase. However, it is common that water enters into the insulation system through failed or broken cladding/jacketing. This is primarily caused by:

- Foot traffic on the cladding/jacketing itself
- Inadequate design
- Incorrect installation
- An insufficient maintenance strategy

When containing hot or cold fluid in a tank, pipe, or other equipment, insulation will be important to avoid heat loss or condensation. These, together with the requirement for protection against potential health, safety, and environment issues, are the main reasons to insulate. However, because of the temperature difference between the insulation and the steel, condensation may occur. This is a potential root cause of CUI. If there is water present, depending on temperature cycling and chemical composition of the water phase, it may develop a very aggressive corrosive environment at the steel surface. The most destructive CUI temperature range for CS is from 60 to 120°C (140−248°F), as the water evaporates at higher temperatures. However, in a closed system, corrosion may occur also at higher temperatures as the vapor may be hindered to escape the insulation by the jacketing. The vapor may condense at the inside of the jacketing and maintains the moist environment. In addition, studies by SigbjØrnsen [3] has shown that the presence of water in insulation even at temperatures in excess of the usual range for CUI occurrence can suppress the temperature of the steel to well within the range of CUI. Therefore areas that were previously left out of risk-based inspection because they had "too high temperature" could indeed be actually corroding due to CUI.

Fig. 17.5 shows the corrosion rate as a function of temperature in an open and a closed system [1]. The closed system shows similar corrosion rate as is measured for CUI. It is observed that although the corrosion rate decreases at higher temperatures for the open system, it increases for the closed system, which is also the case for CUI.

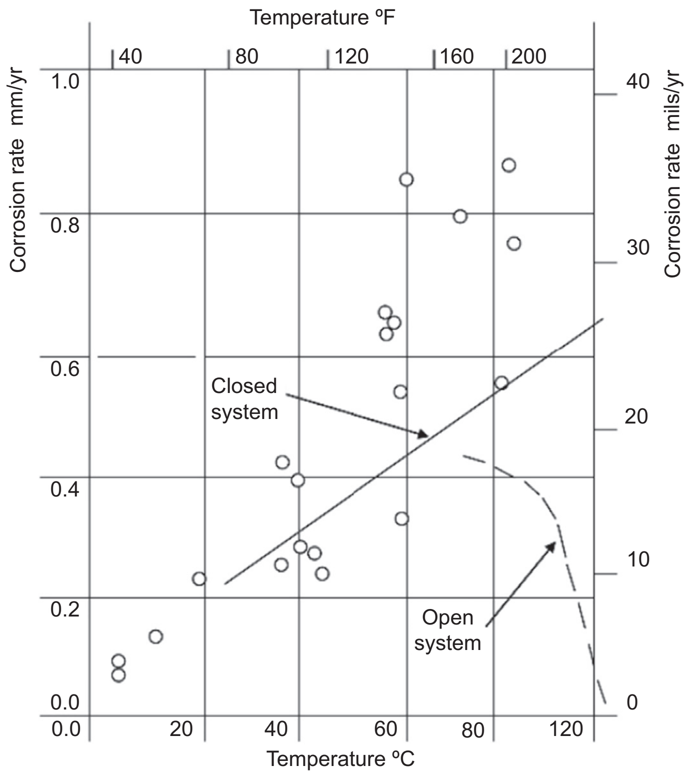

Figure 17.5 Corrosion rate of steel in water at different temperatures, open and closed systems. The plotted *circles* represent field values measured for corrosion under insulation [4].

17.3.2 Insulation solutions

Fig. 17.6 illustrates a typical cross section of an insulated pipe. The choice of insulation does not only affect the ability to maintain the temperature but also the corrosion rate. Typical types of insulation used today are calcium silicate, expanded pearlite, man-made mineral fibers, cellular glass, and organic foams, and ceramic fibers are common insulation materials used by the industry. Some types of insulation, such as phenolic foam and polyurethane foam, contain halides such as chlorides and bromide ions that can dissolve when the insulation is subjected to constant wetting. This will result in a decrease in the pH of the trapped water, which will result in an acceleration of the corrosion rate of the insulated steel. Across the range of insulation types there are also large differences in the wicking properties. For example, calcium silicate, a very popular choice of insulation, may absorb water up to 400% of its own weight, whereas another such as cellular glass (foam-glass) is a nonwicking insulation that will not absorb water, provided that the insulation cell structure is still intact. To add to this, wet calcium silicate has a pH of 9−10, which will create an adverse corrosive environment for coatings such as alkyds and IOZ. Therefore it is critical to

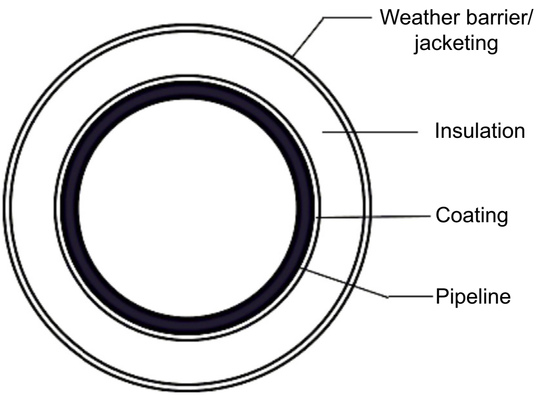

Figure 17.6 Typical cross section of an insulated pipe.

understand that when choosing insulation for austenitic and duplex SSs, the chloride content should be carefully considered because of the susceptibility to chloride-induced stress corrosion cracking.

Insulation materials can be roughly subdivided into permeable (open celled) and impermeable (closed cell) materials. For insulation requirements below ambient conditions, where surface condensation or icing is possible, closed-cell materials such as PUR/PIR foam or cellular glass are often chosen. On the other side of the spectrum for hot systems, mineral wool or expanded perlite are commonly employed.

Another added complication on the choice of insulation to use is the geographical location or for historical reasons. For example, Europe commonly uses mineral wool for hot insulation but in the United States, calcium silicate, perlite, or cellular glass are more common. In specifications, it is a common practice not to refer to product names. Therefore, many insulation specifications refer to general technical requirements such as:

- Water absorption (ASTM C610 or ASTM C612)
- Leachable chloride content (ASTM C871 or ASTM C795)
- Hydrophobicity
- Compressive strength
- Dimensional stability

17.3.3 Insulation jacketing/cladding

In all conventional insulation systems the first line of defense against the environment is the protective jacketing or cladding. This is not only used as a waterproofing system to protect from the ingress of moisture but also protects the insulation system against mechanical damage, chemical attack, and fire damage. Jacketing can come under two basic categories:

1. Metallic jacketing
2. Nonmetallic jacketing

17.3.3.1 Metallic jacketing

Metallic jacketing is predominately formed from thin sheets of 304 SS, aluminum, or galvanized steel with the internal surface coated with a moisture-resistant coating to mitigate corrosion of the jacketing. The advantages of using metallic jacketing are long service life and ease of installation. However, the disadvantages are key to the CUI issues we face today in the respect that they are difficult to seal and are easily damaged from foot traffic often from maintenance and repair operations.

17.3.3.2 Nonmetallic jacketing

Nonmetallic jacketing is generally produced from materials such as thermoplastic materials or fiber-reinforced plastics. They can be used in two forms. Preformed jacketing is usually found in sheet form and, together with the recommended adhesives, can provide water tight seals that are much more resistant to damage by foot traffic than the metallic jacketing. Formed in place jacketing is glass fiber—reinforced epoxy or polyester, which is applied to the outside of the insulation and in the case of the polyester formed into the required geometry before being cured rapidly with UV light.

17.3.4 Coatings solutions

Protective coatings under insulation are effectively used to prevent the contact between the water that has infiltrated through the insulation system and the steel and hence, mitigating corrosion. However, all types of coatings will not have an indefinite lifetime, and there are several limitations to the conditions under which they should be used. In the selection of a coating to protect against CUI, various questions are usually required to be answered:

1. What is the operating temperature?
2. What is the surface preparation?
3. What is the application method?

The most commonly used coating systems for mitigation CUI are the 2-component phenolic epoxies and novolac epoxies. However, process temperatures are increasing, and where 150°C (302°F) was used before, 205°C (401°F) might be used today. This imposes tougher performance requirements for the coatings, and new chemistries for high-temperature coatings were therefore needed to be developed.

Industry guidance, provided by the trade association NACE, holds that immersion-grade protective coatings are the best defense against CUI in both insulated CSs and austenitic and duplex SS. CUI is treated as an immersion condition because of the trapped water under the insulation. Coatings and linings formulated for immersion service are ideal for CUI because the contaminants that pass through the insulation along with the water create an aggressive operating environment. Coating systems incorporated into NACE Standard SP0198-2016 [1] have a track record of success and include 2-component epoxy aluminum or mastics, epoxy phenolics or epoxy novolacs, metalizing or thermal spray coatings, thin film silicones, and organic/inorganic hybrids. A crucial consideration when determining the appropriate protective coating system to use under insulation is the expected service temperature of the equipment or piping, especially when intermittent thermal cycling is present. The coatings on the market are engineered to work at various temperature ranges because one size does not fit all. The most common systems are phenolic epoxies, for temperatures of −45 to 150°C (−50 to 302°F) and novolac epoxies, for temperatures of −45 to 205°C (−50 to 401°F). Additionally, coatings that can be categorized as inert multipolymeric matrix (IMM) or inorganic copolymer (IC) have shown a temperature range from −45 to 650°C (−50 to 1200°F). Modern facilities are running at temperatures as high as 205°C (400°F), where 150°C (302°F) was more standard previously. And although most equipment does not run at the high end of the temperature design, spikes can occur for various reasons and must be taken into account when specifying the appropriate coating system. Coatings suitable for use in oil and gas environments must demonstrate superior resistance to wet/dry cycling. In fact, product testing can involve as many as 30 cycles, 30 days in total duration at 450°C (842°F) dry, and cooling to 23°C (74°F) wet [4], to certify results where rusting, blistering, and coating disbondment do not occur. These coating systems can be used as tank linings as well, so they are immersion grade by their nature. One of the most useful resources within the NACE SP0198-2016 standard itself are the coatings tables, which outline, for given coating system temperature ranges, the recommended surface preparation, surface profile, and categories of prime and finish coats. Table 17.1 "Typical Protective Coating

Table 17.1 Typical protective coating systems for austenitic and duplex stainless steels under thermal insulation [1]

System	Temperature range	Generic first coat	Generic second coat
SS-1	−45 to 60°C (−50 to 140°F)	High build epoxy	N/A
SS-2	−45 to 150°C (−50 to 302°F)	Epoxy phenolic	Epoxy phenolic
SS-3	−45 to 205°C (−50 to 401°F)	Epoxy novolac	Epoxy novolac
SS-4	−45 to 540°C (−50 to 1000°F)	Air-dried silicone or modified silicone	Air-dried silicone or modified silicone
SS-5	−45 to 650°C (−50 to 1200°F)	Inert multipolymeric matrix coating or inorganic copolymer	Inert multipolymeric matrix coating or inorganic copolymer
SS-6	−45 to 595°C (−50 to 1100°F)	Thermal spray Al	Optional sealer
SS-7	−45 to 540°C (−50 to 1000°F)	Aluminum foil	N/A

Adapted from SP0198-2016.

Systems for Austenitic and Duplex Stainless Steels Under Thermal Insulation," and Table 17.2 "Typical Protective Coating Systems for Carbon Steels Under Thermal Insulation and Fireproofing," are both adapted from NACE SP0198-2016 standard. Table 17.2 includes the addition of new protective coating system technologies and

Table 17.2 Typical protective coating systems for carbon steels under thermal insulation [1]

System	Temperature range	Generic first coat	Generic second coat
CS-1	−45 to 60°C (−50 to 140°F)	High build epoxy	N/A
CS-2 (shop application only)	−45 to 60°C (−50 to 140°F)	N/A	Fusion-bonded epoxy
CS-3	−45 to 150°C (−50 to 302°F)	Epoxy phenolic	Epoxy phenolic
CS-4	−45 to 205°C (−50 to 401°F)	Epoxy novolac or silicone hybrid	Epoxy novolac or silicone hybrid
CS-5	−45 to 595°C (−50 to 1100°F)	Thermal spray Al	Optional sealer
CS-6	−45 to 650°C (−50 to 1200°F)	Inert multipolymeric matrix coating or inorganic copolymer	Inert multipolymeric matrix coating or inorganic copolymer
CS-7	60°C (140°F) maximum	Thin film petrolatum or petroleum wax primer	Petrolatum or petroleum wax tape
CS-8 inorganic zinc shop-primed pipe	−45 to 400°C (−50 to 750°F)	N/A	Typically coatings from system CS-3/4/6
CS-9 under fireproofing	Ambient	Epoxy or epoxy phenolic	Epoxy or epoxy phenolic
CS-10 galvanized steel under fireproofing	Ambient	Epoxy or epoxy phenolic	Epoxy or epoxy phenolic

Adapted from SP0198-2016.

elimination of outdated ones, the addition of metallic coating systems, and a modification of the recommendation for new bulk piping that is primed with an IOZ-rich coating. This standard has just been reaffirmed and reissued in 2016. Although it is common in the oil and gas industry to use a shop-applied IOZ coating as a primer on new CS piping because it dries quickly and is cost-effective, IOZ provides inadequate corrosion resistance in closed, sometimes wet, environments. At temperatures greater than 60°C (140°F), the zinc may undergo a galvanic reversal where the zinc becomes cathodic to the CS. Shop-primed pipe will be finish-coated at the job site depending on the service conditions needed.

The standard recommends top coating the IOZ to extend its service life, and that it is not be used by itself under thermal insulation in service temperatures up to 175°C (347°F) for long-term or cyclic service. In cases where pipe is previously primed with an IOZ coating, it should be top coated to extend its life. The CS coatings table in the NACE document should be referenced, and the coating manufacturer should be consulted for the generic coating, dry film thickness (DFT), and service temperature limits.

17.3.4.1 Epoxies

Conventional epoxies have been used for many years in the form of aluminum pigment filled or "mastic" formulations. These were generally high-solids materials, i.e., >80% volume solids and performed adequately up to temperatures of 120−150°C (248−302°F). To this date many specifications still use conventional epoxies as part of the solution to combating CUI. However, as previously mentioned, the push to higher process temperatures has seen the demise of these types of coatings. They have been replaced by either the phenolic or novolac epoxies for temperatures up to 205°C (401°F) or by modern organic/inorganic hybrids for higher temperatures.

17.3.4.2 Metallic coatings

Thermally sprayed aluminum (TSA) is a very common metallic coating used for CUI. TSA has a maximum operating temperature of 595°C (1103°F), and it has no limit to the surface temperature when it is applied, as it is arc or flame applied. SSPC-SP10, near-white blast cleaning, is needed as surface preparation. The application and surface preparation are crucial for the corrosion-resistant properties of the TSA, but when correctly applied, it has demonstrated a lifetime of 20 years with no maintenance. In rural areas it will not function as a sacrificial anode, but in marine environments containing chlorides it will have this effect.

A protective layer of Al_2O_3 is formed at the surface and slows down the corrosion rate. However, TSA has a porosity of 5%−15%, and therefore sealer paints are often applied as a final coat, because the porous surface forms a good base for the paint.

Zinc has a thinner passive film area in a chloride-containing environment and will therefore often be an active layer, which implies higher corrosion rate. When using zinc as protection against corrosion, the film will thus corrode away after much shorter time than the TSA coating. Also it has been found that for temperatures higher than approximately 60°C (140°F), the corrosion potential for zinc increases more than that for iron. There is no reversal in the standard electrochemical potential between zinc and iron, but in closed-circuit conditions, corrosion products will form at the zinc surface but not on the iron surface, and the corrosion potential for the zinc will become greater than for the iron. This implies that zinc will transform from sacrificial anode to cathode with respect to the CS substrate [5]. However, this is dependent of the presence of dissolved oxygen, temperature, and the composition of the water. This should be taken into account when using zinc for cathodic protection. For an insulated surface, NACE SP0198-2016 stipulates that zinc should not be used at temperatures 50−175°C (120−347°F). The maximum DFT of many zinc silicates is 75 μm (3 mils), which is not sufficient for protection against CUI. The extremely harsh corrosion conditions observed under insulation will accelerate the corrosion rate of zinc. If steel is primed with an IOZ-rich material the coating should be top coated to extend the service life.

17.3.4.3 Epoxy phenolics/novolacs

Epoxy phenolic coatings are known to perform well beneath insulation but have a limited temperature resistance to around 205°C (401°F). On CUI pipe testing [4] the epoxy phenolic coating performed well at the lower temperature end of the pipe; however, the portion that was subjected to temperatures above 230°C (446°F) showed the coating degrading, flaking off, and allowing corrosion to take place. This correlates exactly with the performance that is seen of epoxy phenolics in the field. They provide good long-term protection against CUI up to 205°C (401°F) but are destroyed when subjected to high-temperature cycling, subsequently allowing corrosion to take place. Some phenolic epoxies are also used, and the coating tested has a higher maximum operating temperature of 230°C (446°F). At these higher temperatures, typically, the coating will become brittle and crack. Phenolic epoxies normally have a narrow DFT range, and it must not exceed 300 μm (12 mils) to avoid cracking. Typically, two coats of 100 μm (4 mils) each are used. The application temperature should not be less than 3°C (37°F), and temperatures lower than 10°C (50°F) result in longer curing times.

17.3.4.4 Aluminum silicones

Silicone-based coatings are formed when inorganic silicone pigments are added to a coating. They have high operation temperature limit and high resistance against moisture and weathering. However, they are somewhat expensive and will not withstand acids and alkalis. Several types of silicone-based coatings have been developed. IOZ silicate coating can endure temperatures up to 400°C (752°F), but because of unsatisfactory long-term corrosion resistance it is not used for CUI. Also the thermal cycling and shock properties of these early silicon-based coatings are poor.

Aluminum silicone coatings are another commonly used elevated temperature technology and are generally applied in two or three thin coats of 25 μm (1 mil) each.

Industry has learned that these coatings do not provide adequate protection against CUI because of their thin films and limited barrier protection, despite being able to withstand temperatures up to 540°C (1004°F).

17.3.4.5 Organic/inorganic hybrids

The first of these types of coatings were introduced in the mid-1990s and were plagued with issues of film microcracking and hence did not live up to their original performance aspirations. These types of products are no longer present and have been replaced with more robust coating systems. The next-generation inorganic/organic hybrid CUI coatings have been developed and are in use since the turn of the century and were dominated by two chemistry types:

- TMIC/IC, titanium modified inorganic copolymer/inorganic copolymer
- IMM, inert multipolymeric matrix

These types of products are now used in CUI operations across the full CUI temperature range and beyond. The chemistry used allows cryogenic usage as well as temperatures in excess of 600°C (1112°F) in the case of the IMM coatings. The first generation of IMM coating materials provided an improved solution for CUI, but a few limitations were spotted. Prolonged dry time to handle and poor sprayability (overspray) have been the main drawbacks in terms of application features. Poor mechanical resistance (softness, poor flexibility, and poor impact resistance) is the other key drawback, making shop-painted steel prone to damage during transportation from shop and at erection on site.

A second generation of IMM coating has been developed, and it has been used in the field since 2012. This second-generation IMM overcomes the drawbacks of the earlier generation.

17.3.4.6 Insulation coatings

An alternative coating solution to mitigate CUI is to install spray-applied, nonclad thermal isolative coatings that provide a monolithic barrier to water, chemicals, UV rays, and heat transfer. Such sprayable insulative coatings (SIC) provide personnel burn protection, thermal insulation for energy conservation, and protection from radiant solar heating. Coatings companies have worked to develop multipurpose insulative acrylic coating engineered to optimize thermal properties. These products enable dangerously hot systems such as piping and ductwork to stay cool to the touch, preventing burns and protecting the safety of personnel. They can be applied directly to ambient or hot surfaces offering facility operators the chance to reduce downtime by keeping systems online during coating. Such coatings are suitable for any industry where conventional insulation and cladding are required. To date, this type of technology does not cover the full range of operative temperatures and insulation needs, as the cladding approach does. But it is already able to replace cladding systems in a number of scenarios, as a viable option for providing insulation while effectively removing the source of the CUI phenomena.

Table 17.3 A generic snapshot of the technology and a list of the utilization scenarios for SIC

Snapshot	• Industrial WB acrylic resin with engineered ceramic microspheres • Low thermal conductivity (0.097 W/m × K) • Lightweight due to high air content • Expected service life of 10−20 years with recommended primers and topcoat	
Uses	Replacement for conventional insulation and cladding Personnel protection coating Hot or cold process insulation Control radiant heating of storage containers	Service temperature range (all applications) from −51°C (−60°F) to 177°C (351°F)

Table 17.3 provides a generic snapshot of this technology and lists the range of utilization scenarios that SIC can cover today, at current stage of development of the technology, using waterborne acrylic resins with ceramic microspheres.

Formulated from waterborne acrylic resins with ceramic and glass microspheres that minimize energy transfer through the film because of its high air content, these coatings adhere to the underlying primer and prevent water or moist air from corroding the steel.

The air content is so high in these coatings that the specific weight of the liquid paint typically ranging from 0.6 to 0.7 Kg/L, with an important fraction of that weight evaporating out during the drying process.

17.4 Vapor-phase corrosion inhibitors

Vapor-phase corrosion inhibitors (VCIs) are completely different alternative protection method to that of coatings. A VCI is a volatile chemical compound that forms a stable bond at the interface of the metal, preventing penetration of corrosive species to metal surfaces. These inhibitors are easy to apply and can be used to protect a selection of metal types used in various corrosive environments. VCIs work through a series of chemical characteristics:

- Stable metal passivation
- Strong surface adsorption properties
- Excellent surface wetting properties
- Thermally stable to 176°C (349°F)

When applied usually by injection into the insulating jacket either through a gravity feed system or a portable injection pump, they form a clear, dry, hydrophobic film of approximately 6 μm (0.24 mils).

17.5 Nondestructive inspection techniques to prevent CUI failures

The real issues with CUI is the fact that the only 100% certain way of knowing that there is no problem on pipes and vessels is to completely remove the insulation system. This is not the approach that corrosion engineers/end users wish to adopt because it is also the most expensive way of inspection. This created a challenge for researchers to provide techniques that eliminate the need to completely dismantle insulation systems for inspection. The techniques are required to be nondestructive (NDE) technologies and portable to be used on site. These techniques can be used along with conventional techniques to provide economical, comprehensive CUI inspection of piping networks. Some of the proven NDE techniques are as follows:

- Neutron backscatter
- Infrared (IR) thermography
- Guided wave ultrasonic technology (UT)
- Profile radiography
- Computed radiography (CR)
- Pulsed eddy current (PEC) testing

Out of these methods, profile radiography and guided wave UT are accepted in API 581 [6] as alternatives to insulation removal for inspection.

17.5.1 Neutron backscatter technique

It is effective in scanning large areas of pipe to determine wet/saturated insulation in a short period of time. It uses a radioactive source that emits high-energy (fast) neutrons into desired location of insulation. The high-energy neutrons travel through the insulation and collide with light elements such as hydrogen transforming into low-energy neutrons. A sensitive detector designed to detect low-energy neutrons is used to identify the “wet insulation” by measuring the count of low-energy neutrons. The count is proportional to the amount of water in the insulation and therefore could potentially signify a potential for CUI. This technique is a quick and accurate way to identify potential areas where CUI could occur. It is very portable and, in some cases, will negate the need for scaffolding. However, it does require a radiation source with the associated health and safety issues, and it will not directly detect CUI.

17.5.2 Infrared thermography

IR thermography can be effectively used to identify wet insulation in pipelines and is much more effective than traditional moisture density gauges in addition to being a much faster technique. An added benefit is that pipelines can be scanned with this technique from a distance, negating the need for costly and time-consuming construction of scaffolding. Inspections can be carried out on either heat-traced or nontraced insulated pipelines. The technique is dependent on the fact that wet insulation retains heat longer than dry insulation, and therefore carrying out the inspection after sunset or when the pipelines are shaded will allow the inspector to distinguish between hot wet lines and cooler dry lines. Because the temperature between wet insulation and dry insulation is not large, it is recommended as best practice to use a small temperature span to increase the sensitivity of the technique.

17.5.3 Long-range ultrasonic testing

The use of guided waves in long-range ultrasonic testing (LRUT) to scan pipelines is particularly useful for the inspection of pipelines that are otherwise inaccessible for inspection. The ultrasonic waves are transmitted into the pipe wall from a loop of equally spaced ultrasound probes supported by a collar wrapped around the pipe. Once traveling along the pipe the ultrasonic waves are reflected by discontinuities such as girth welds, branches in pipeline circuit, and, more importantly, reductions in wall thickness. These reductions in wall thickness are associated with areas of corrosion, and once detected they can be analyzed via computer software.

LRUT can typically scan a length of straight pipeline up to a maximum 120 m. However, this will be reduced dependent on the type of insulation on the pipeline and the complications on the line such as supports, connections, and bends. Even so, LRUT is considered one of the most effective tools in identifying CUI in pipelines where removal of insulation is difficult.

The interpretation of LRUT can be complicated in comparison to the aforementioned IR technique and therefore is best used with trained specialists. However, it is recognized as one of the most reliable techniques to carry out the inspection of insulated pipelines in hard-to-access or inaccessible locations, especially lengths of pipeline passing under inaccessible culverts, buried piping, and at road crossings.

17.5.4 Profile radiography

Profile radiography is a technique that allows the internal wall thickness reduction of small diameter 8″pipelines to be inspected. For this reason it can also be used to find CUI as long as the source to film distance is sufficient to assess the entire line diameter in one measurement. When the pipeline diameter is more than 8″ then multiple measurements will be required to cover the full pipe diameter. The obvious disadvantage of this type of technique is the requirement of a radioactive source and the associated health and safety issues.

17.5.5 Computed radiography

This technique uses equipment similar to that used by conventional radiography except that in place of a film to create the image, an imaging plate is used. To fully exploit this technique for the detection of CUI under insulation, effective segregation of the target area is required to remove interference from pipe supports and the like. The images produced and data obtained from inspection is stored digitally, and hence the data can be accessed quickly to aid increased inspection efficiency.

17.5.6 Pulsed eddy current

The PEC has been a popular choice for inspection for a number of years and uses the principle of eddy currents. It consists of a probe that contains a transmitter and receiver. The transmitter is basically a coil to produce eddy currents in a conductor, typically a metallic substrate, i.e., pipeline or vessel. This method is a noncontact electromagnetic method for the determination of average wall thickness. The system works via a probe coil generating a magnetic field, which is used to magnetize the target substrate. This generates eddy currents in the pipe wall and thus diffuses inwards. If there are anomalies detected the eddy pulse is stopped, causing a sudden fall in the applied magnetic field. This is picked up by the PEC receiver probe. The thicker the pipe wall thickness, the longer it takes for the eddy currents to bounce back from the back wall of the metal. Using this data then, corrosion can be calculated as a percentage reduction in pipe wall thickness. This technique is not restricted by insulation material and can be used in situ up to operating temperature in excess of 450°C (842°F). The downside of this technique is its sensitivity. Compared with the radiographic technique it is relatively low because of the footprint of the test and therefore is predominantly used for wall loss measurements rather that the pitting corrosion caused by isolated CUI.

17.6 Knowledge gaps and future trends

Although the problem of CUI has been documented for decades, there are still numerous avenues of research remaining, to further prevent the effects of CUI. The key areas of research to fill the knowledge gaps in the oil and gas industry can be split into three categories.

17.6.1 Development of new CUI coating technologies

At present, as previously mentioned, there are numerous coatings for the mitigation of CUI, but all have their particular advantages and disadvantages. There are some key coating properties that all coating suppliers are trying to improve to further enhance coatings performance:

- Mechanical properties both before installation and in-service
- Temperature resistance both isothermal and cyclic
- Substrate tolerance
- Ease of application, one component versus two components
- Corrosion performance
- HT immersion resistance

It is not enough to focus on one of the aforementioned properties, but the coating supplier needs to address as many of them as possible to advance the coating performance. Developments in IMM have been achieved from the initial formulas and have gone a long way to address the issues mentioned. There have also been recent developments in increasing the temperature resistance of epoxy chemistry to beyond previous limits as referenced in NACE SP0198-2016 [1] of 205°C (401°F), reaching up to 250°C

(482°F) in some cases. However, as with all new developments that change the boundaries of known performance, long-term data is not available, and therefore these epoxy new based coatings need to be proven before they should be widely specified.

17.6.2 Development of new test methods

The knowledge of how coatings perform in the CUI environment is still not fully understood. This means that the ability to predict the performance of a coating in the field compared to accelerated laboratory test data is still not at a high level of confidence. As previously mentioned, there are multiple committees, standards, and JIPs by various groups, but until now there is no sight of agreement on a test or test methods.

The key issue facing the test method developers is to reproduce the extent of failure seen in CUI, which means that severe pitting within the most destructive CUI temperature range for CS (60 to 120°C (140−248°F)). However, this has to be reproduced in weeks or months, and not years, and has to include all the elements of the insulation system i.e., insulation and jacketing. One of the key issues in previous years has been the ability of the coating manufacturers to access trial areas in oil and gas facilities, which has been difficult. The importance of this type of correlating data has now been recognized with some major oil and gas producers who have now actively carried out research in CUI testing.

The key influencing group at present is NACE Task Group 516 (TG516), which has been set up to assess all currently published CUI test methods and to develop a new standard for the prequalification of coatings for use under insulation and consistently is attended by over 30 worldwide technical professionals to discuss new test methods. A committee for the TG has been formed, comprising coatings suppliers, testing companies, and end users to finalize this as a testing protocol to approve coatings for use under insulation.

17.6.3 New insulation developments

The development of insulation coatings is being concentrated into two main routes

- Higher temperature resistance
- Ability to apply higher film build in less coats

Current technologies for atmospheric liquid insulation are hampered by their chemistries. Generally, technology available today is based on either waterborne acrylic technology that has temperature limitations to 177°C (350°F) or epoxy syntactic materials with temperature limitations of 200°F (392°F). In the cases of the waterborne acrylic and the epoxy the temperature resistances come from the binder resin. The waterborne acrylic also has issues with the need for multiple coats at 300−500 μm (12−20 mils) and because they are waterborne, the epoxy can be applied at >5000 μm (200 mils) per coat. New potential technologies to try to alleviate the issue are based on solvent-borne or solvent-free materials, using silicon or polysiloxane technologies, which have been shown for many years to have better thermal stability.

Significant advances in insulation technology have been observed in the materials added to binder systems to impart thermal insulation performance. Traditional glass or polymer beads in insulation formulations have been replaced with materials such as aerogels, nanogels, and hollow oxides.

However, even with significant progress, no material has yet solved both high-temperature resistance and high build requirements.

Appendices

Standards committees/forums

There are various active NACE committees that share knowledge and experience in the industry. These are very well attended by all types of professionals:

a. Major oil companies
b. Engineering procurement and construction companies (EPCs)
c. Coating suppliers
d. Coatings test companies
e. Academics

The current committees are listed below.

NACE TEG 351X—Advances in Coatings Under Insulation (CUI) Technologies

Assignment: Discussion of the development of recommended test procedures for qualification of coatings used under insulation service.

NACE TEG 399X—Evaluation, Testing and Specifying Coatings Materials for Elevated Temperatures for Insulated and Uninsulated Service

Assignment: Exchange information, create task group for state-of-the-art report followed by formation of a task group to write a standard practice, and sponsor symposium.

NACE TG 325—CUI: Reaffirmation of NACE SP0198 (formerly RP0198), "The Control of Corrosion Under Thermal Insulation and Fireproofing Materials—A Systems Approach"

Assignment: To reaffirm NACE SP0198 (formerly RP0198).

NACE TG516—Standard Practice for Evaluating Protective Coatings for Use Under Insulation

Assignment: To write a standard practice for testing coatings for CUI prevention.

International Organization for Standardization, ISO

The formation of ISO committee to look at the development of a test method for prequalification of coatings for CUI is a relatively new development and is again attended by the same industry professional as for NACE, indeed some of the same experts.

European Federation of Corrosion, EFC

The European Federation of Corrosion, EFC, Working parties WP13 and WP15 have worked to provide guidelines on managing CUI together with a number of major European refining, petrochemical, and offshore companies. The guidelines within this document are intended for use on all plants and installations that contain insulated vessels, piping, and equipment. The guidelines cover a risk-based inspection methodology for CUI and inspection techniques (including nondestructive evaluation methods) and recommend best practice for mitigating CUI, including design of plant and equipment, coatings and the use of thermal spray techniques, types of insulation, cladding/jacketing materials, and protection guards. These are available in the "Corrosion Under Insulation (CUI) Guidelines (EFC55)" [7].

Test methods for prequalification of test methods

Although there is no dedicated standard to prequalify CUI coatings, there has been a lot of effort from various sources in trying to simulate the type of failure on a laboratory scale. It is fundamental to understand that this is not an easy task, and this is why today we still do not have one test, or a series of tests, which is fully endorsed by all interested parties. Some of the most reported test methods are given below in brief.

- ASTM G189—Laboratory Simulation of Corrosion under Insulation [8]

  This guide covers the simulation of CUI, including both general and localized attack, on insulated specimens cut from pipe sections exposed to a corrosive environment usually at elevated temperatures. It describes a CUI exposure apparatus, preparation of specimens, simulation procedures for isothermal or cyclic temperature, or both, and wet/dry conditions, which are parameters that need to be monitored during the simulation and the classification of simulation type.
- ASTM D2485—Evaluation of coatings for elevated temperature service [9]

  This test method covers the evaluation of the heat-resistant properties of coatings designed to protect steel surfaces exposed to elevated temperatures during their service life. Two test methods are described as follows:
  - Method A—Interior Service Coatings
  - Method B—Exterior Service Coatings
- K. Haraldsen, Statoil Test Method 2010 [10]

  The test cell consisted of test spools of coated CS tube sections flanged together in open containers. The containers are filled with seawater and then drained immediately after the spools were fully submerged, taking in the order of 20 min to complete. The spools were heated internally via steam to 140°C (284°F). The cycle was carried out three times per week. After testing to varying periods of time the coated spools were evaluated for rusting, blistering, and cracking.
- CUI Cyclic Corrosion Pipe Test (CCCPT) [4]

  A coated pipe is insulated with calcium silicate, sealed with aluminum foil, and placed on a hot plate at a temperature of 450°C (842°F) with the top of the pipe measured at approximately 60°C (140°F). The system is cycled 30 times with 8 h of heating followed by 16 h of natural cooling. Before and after each heating cycle the insulation is wetted with 1 L of 1% NaCl solution. The coatings are evaluated for rusting, blistering, and cracking.
- HTC Cell [11]

  The heart of the HTC environmental test is the heat exchanger, cell, and chamber. The coated cell is a carbon or SS 4″ × 4″ square pipe section 24 in. long with a 1/4 in. wall thickness. The cell is placed horizontally in the chamber in a closed-loop system. Hot oil from a heat exchanger is circulated through the cell, and the temperature is controlled from ambient to 250°C (482°F). No insulation is used for this test allowing the flexibility for immersion testing, and the test media can be modified on agreement of the end user. The bottom portion of the cell is under continuous immersion for the duration of the wet cycle. The test protocol is set for alternating wet and dry 4-h cycles. The vertical surface is scribed to the substrate to asses undercut corrosion evaluation.

- CUI Simulation test [12].

  This test method is intended to test a coating that has been designed to prevent corrosion under thermal insulation.

  The coatings under test are applied to steel panels in duplicate (3″ × 6″ panels are recommended) to both sides of the panels. The edges of the panels are sealed, and the panels are allowed to cure for 7 days at ambient conditions or heat cure according to manufactures recommendation. The coated panels along with an uncoated panel are placed between pieces of insulation, mineral wool, or calcium silicate, which have been cut to fit a stainless steel pan. The pan is then covered with aluminum foil and placed in an oven maintained at 350°F (177°F) for 7 days. After 7 days, remove the pans from the 177°C (350°F) oven, saturate the insulation with tap water, and reseal, maintaining saturation during the entire 7-day period. Place the pans into an oven maintained at 66°C (150°F) for 7 days. After testing, the coated panels are evaluated for rusting, blistering, and cracking.

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