

TECHNICAL PAPER

Corrosion Under Insulation

A holistic approach to insulation system design to reduce risk of CUI on industrial piping.

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ABSTRACT

Corrosion Under Insulation (CUI) on industrial piping is a major issue for the oil and gas industry. The potential influence of thermal and acoustic insulation materials is normally assessed through a series of individual laboratory tests on the insulation materials themselves, but very rarely on the applied system. Moreover, the tested physical values do not necessarily and readily reflect the potential influence that a given insulation material or system has on the risk of CUI.

A more sophisticated approach is proposed which takes into account not only the applied insulation system, but also the CUI failure behaviour and water or water vapour ingress and retention processes. This approach allows the individual risk assessment of the

applied insulation systems against different scenarios of water ingress to be performed.

Other influencing factors for the risk assessment include the configuration of the insulation system (e.g. insulation materials, aluminium barrier foil, outside claddings) and specified construction or installation methods.

It is hoped that the approach proposed in this paper will enable the reader to improve their knowledge of insulation materials and their influence on CUI risk and furthermore, be able to better identify vulnerable areas on the facility where CUI is likely to occur, thereby allowing appropriate CUI management strategies to be developed and implemented.



INTRODUCTION

The World Corrosion Organization estimates that corrosion costs the global economy \$2.2 trillion annuallyⁱ. According to its figures, almost 45 percent of the cost of this corrosion – about \$1 trillion – happens in the oil, gas and petrochemical industries impacting onshore and offshore operations. Corrosion Under Insulation (CUI) is widely acknowledged to be a critical issue facing plant operators.

It is estimated that 40-60% of pipe maintenance costs are a result of CUI, and 10% of total annual maintenance costs in these industries is dedicated to repairing damage caused by CUI^{ii,iii}. Severe cases of CUI may put personnel, environment and industry reputation at risk. Despite the numbers and awareness when it comes to insulation materials little research exists into the best method of preventing CUI to extend the pipework's life and optimise safety.

Insulation is primarily installed for heat/cold conservation, frost protection, process control, personnel protection, sound control, condensation control or fire protection. The type of insulation selected is recognised as having an important role in the overall ability of the system to mitigate against CUI. It has been identified, for example, that the following material characteristics have the most influence on CUI: closed and open cell (porous) nature of the insulation material, water absorption, permeability and retention, water wicking, levels of leachable chlorides and the choice of cladding^{iv}.

Insulation alone cannot safeguard plant components against corrosion, but appropriate insulation systems can effectively support corrosion mitigation. The choice of the insulation system determines whether the insulation withstands water or water vapour ingress and minimises the risk of corrosion, or allows or even potentially accelerates corrosion processes.

This white paper is designed to enable the reader to improve their knowledge of insulation materials and their influence on CUI risk and furthermore, be able to better identify vulnerable areas within a facility where CUI is likely to occur, thereby allowing appropriate CUI management strategies to be developed and implemented.



WHAT IS CORROSION AND CUI?

Corrosion is usually the result of an electrochemical process that takes place when water combines with oxygen at a metallic surface (such as a pipe or vessel). Corrosion begins when an electrochemical potential is established at two or more locations on the metal surface, or between two separate metallic components (such as the steel pipe and metal cladding). The electrochemical potential causes local deterioration at the anodic site which results in metallic substances (typically oxides, sulphides and hydroxides) being dissolved into water and deposited as rust on the cathodic site.

CUI is any type of corrosion that occurs on the pipework due to the presence of moisture within or under the insulation system. That insulation may be applied for thermal or acoustic purposes and is especially prevalent in the oil and gas sector, where steel pipework is used extensively, and because facilities tend to be located in geographical regions that are conducive for CUI. These include marine and offshore, hot/humid and high rainfall environments. In addition, operating conditions may create temperature cycles that lead to a build-up of water within the system and create temperature regions where CUI is exacerbated.

// When does CUI occur?

Multiple factors can influence the development of CUI. Important factors are temperature (operating and ambient) and water (in liquid or vapour state and from different sources). Other factors which may also have an influence on CUI include contaminants in the water, trapped both within and under the insulation system (e.g. chlorides or sulphides, coming from the atmosphere or leaching from the insulation), the type of insulation material, the choice and condition of the protective jacketing and vapour barriers, intermittent wet-dry environmental conditions, moisture trapped within the insulation material (due to incorrect storage/application procedures), pipe surface coating or preparation, and the insulation system design, among other factors^{iv}.

CUI develops when the metal is exposed to water over a period of time and is possible under all types of insulation materials (these include, but not limited to: calcium silicate, expanded perlite, man-made mineral fibres, aerogels, cellular glass, and organic foams, which includes: Polyurethane foam (PUR), Polyisocyanurate (PIR), Flexible Elastomeric Foam (FEF), phenolic (PH) and expanded/extruded polystyrene (EPS/XPS). For a given steel type and coating, the corrosion rate will be affected mainly by quantity of water containing corrosive contaminants and the temperature of the pipework.

// Influence of water and moisture on CUI

For CUI to occur on carbon or low alloy steel, water or moisture must be present. Liquid water ingress may occur due to rainwater or deluge systems, process liquid spillage or condensation; and it can enter in through the insulation cladding / jacketing as a consequence of poor installation / damage during service or simply due to its gradual deterioration^{iv}. Depending on the properties of the insulation material and the operating temperature, this water may be retained and the insulation system can get saturated, which in addition to corrosion may result in a loss of thermal and/or acoustic performance.

CORROSION UNDER INSULATION ON INDUSTRIAL PIPING

The role of insulation in the development of CUI is threefold^{iv}. It provides:

- An annular space or crevice for the retention of water and other corrosive media
- A mechanism for moisture to be absorbed and spread through by a process of “wicking”
- A means of contributing contaminants (e.g. leachable chlorides) to accelerate corrosion rates.

Separate from liquid water ingress is the phenomenon of water vapour diffusion which when active leads to further uptake of water into the system. Water vapour diffusion occurs when water molecules present in the atmosphere migrate towards the surface of the pipe due to the lower partial pressures established when service temperatures are below ambient. The performance of an insulation material with respect to water vapour ingress is determined by its water vapour diffusion resistance which differs with insulation type.

For traditional porous insulation systems, water may easily wick through the insulation layers causing CUI to spread rapidly around and along the length of the pipe. Alternatively, closed-cell insulation materials reduce the spread of CUI by restricting water vapour ingress through its entire thickness.

// Influence of temperature on CUI

Organisations dealing with CUI within the oil and gas sector broadly agree that the risk of CUI on carbon steel increases when the service temperature ranges from just below the freezing point of water to 175 °C (347 °F).

An overview of the CUI risk profile as a function of temperature given in guidance documents issued by the organisations: NACE^{iv}, CINI^v and API^{vi} is presented in **Figure 1**. This shows that the risk of CUI is increased for temperatures from 50 °C (122 °F) to 175 °C (347 °F), and according to the recommended practice of API, is especially critical between 77 °C and 110 °C (171 °F to 230 °F).

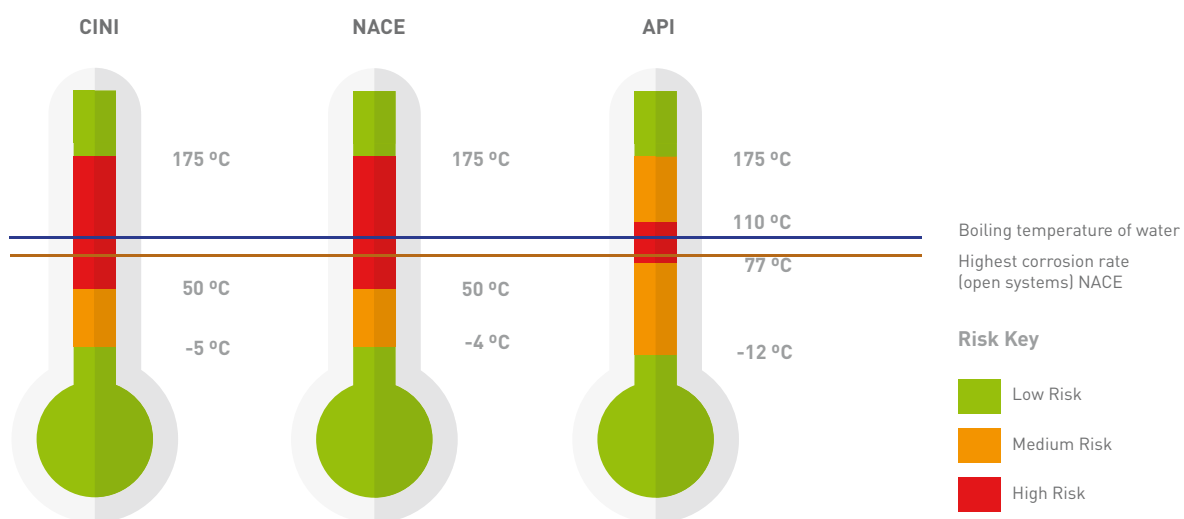


Figure 1. CUI risk profile as a function of temperature

CORROSION UNDER INSULATION ON INDUSTRIAL PIPING

For some insulation systems, the critical temperature range is further narrowed by NACE who declare that the corrosion rate of carbon steel in the presence of aerated water reaches its maximum temperature from at or around 80 °C (176 °F)^{vi}. At this temperature very high corrosion rates of up to 0.5 mm/year (0.016 in/yr) at 80 °C (176 °F) can be expected^{vii}.

Determining the critical temperature range for CUI is important when developing methods for assessing the performance of insulation systems. Temperatures should be high (to accelerate the chemical reaction of corrosion), but not too high so that water present in the system cannot evaporate too readily. In the case of both our previous white papers^{viii, ix}, the operating temperature of the equipment was selected to run for periods of time at the critical temperature of 80 °C (176 °F). This represented a regime where CUI was most likely to rapidly occur and thereby making it the most challenging condition in which to assess the performance of the insulation materials.

// Influence of temperature cycling on CUI

Cycling temperature conditions present additional challenges due to the regular supply of water vapour into the insulation system during any cold temperature phase (or shutdowns) depending on the cycling regimes. Water vapour ingress may occur because of the partial pressure difference between the outside (high pressure) and inside (low pressure) of the insulation. The cycling also leads to the deposit and accumulation of salts, along with other corrosive ions, which remain within the insulation and on the surface of the pipe when the water evaporates during each high temperature phase. The impact of corrosive ions is discussed in the following section.

// Influence of leachable ions on CUI

Insulation materials may contain chlorides and fluorides which contribute to corrosion when deposited and concentrated on the pipe surface. The presence of leachable ions is of particular concern in the case of external stress corrosion cracking (ESCC) on austenitic stainless steels. Many insulation specifications determine that the concentration of leachable ions should not exceed 90ppm^v, although lower limits may be requested for open cell (porous) insulation where leachates can generally travel more easily to the surface of the pipe.

While the selection of materials are an important consideration, it should be appreciated that arguably the more significant source of corrosive ions is directly from the environment in which the materials are installed. This is especially the case when located in offshore or coastal regions.

CUI PREVENTION - A SYSTEMS APPROACH

For many years, experts have sought to prevent or mitigate the onset and development of CUI by focusing on technologies that protect the pipe surface and improve the inherent resistance of the steel-work used. While this makes complete sense, until recently very little work has been performed to evaluate the influence that the type and design of the insulation system itself plays in the CUI story.

The danger with failing to properly consider insulation in the strategy against CUI is that there is a tendency to assume that all insulation systems will perform similarly and that it doesn't matter what insulation you use, because water is always going to reach the pipe surface and corrosion will occur. This argument is based, in part, on the fact that the law of entropy determines that all things must corrode eventually.

However, the whole premise of CUI mitigation is that we are seeking to delay or slow the onset, spread and development of CUI. When we start to think about all components of a system playing a part in the defence against CUI, we start to realise that there are a greater number of opportunities for building more reliable strategies against it. Careful consideration to material selection is just as important for the insulation material as it is to the protective coating. If corrosion is inevitable, why do we bother with coating the pipe? The simple reality is that the application of a coating will delay the onset and spread of CUI and this is precisely what a properly designed insulation can help to achieve.



CUI DEFENCE MECHANISMS

We may consider that altogether there are 5 lines of defence at work to mitigate CUI:

1. The type and grade of steelwork (pipe/vessel)
2. The protective coating
3. The insulation layers
4. The vapour barrier
5. The cladding / jacketing / covering

Figure 2 illustrates how these 5 lines of defence fit together in the context of the complete system

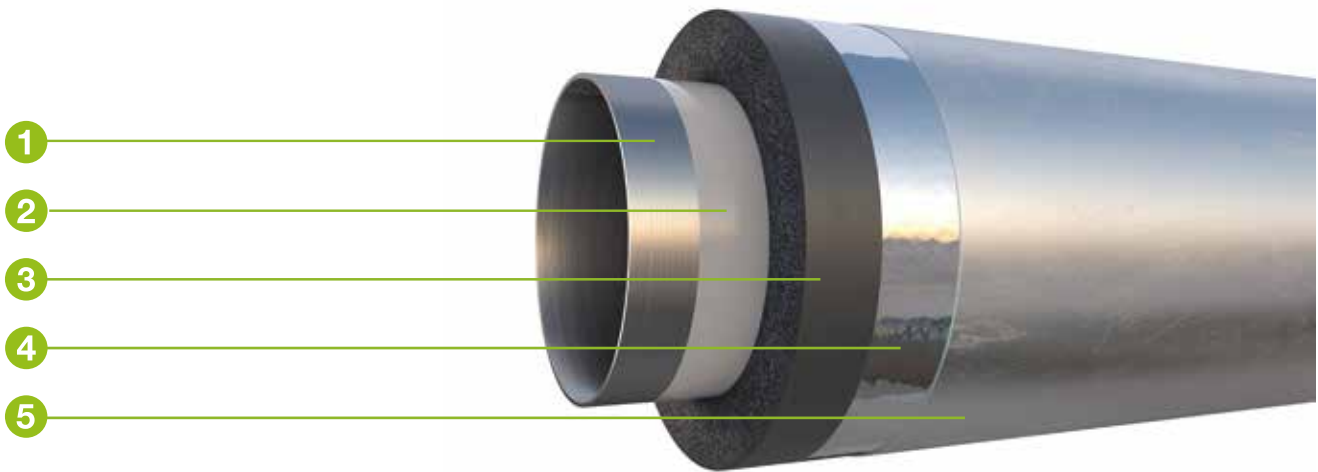


Figure 2: Annotated diagram showing the 5 lines of defence in a system designed to mitigate CUI.

Each line of defence has performance limits and all are susceptible to design and application errors, which from a practical perspective present the most significant challenge when it comes to the performance of a system against CUI. We may consider that where errors/defects do occur in any line, so long as the other lines are functioning as intended, the performance of the whole system to mitigate CUI is not necessarily compromised.

By way of example, we can consider that the first line of defence is the cladding (which includes banding, clips, mastic sealants, adhesives, etc.). The cladding is directly exposed to the surrounding environmental conditions and, where installation errors have occurred or indeed where sections have been damaged in some way (e.g. by persons walking on the pipework), it will inevitably fail at some locations. In the case of metallic jacketing, it is not unusual for the vapour barriers which are installed beneath as a second line of defence, to be ruptured and damaged at the same time.

The third line of defence is the insulation and the focus turns to the insulation materials' inherent ability to resist the entry and spread of water or that of water vapour and its retention. Materials with high resistance to water and water vapour ingress will, at the very least, delay the time it takes for water to reach the surface of the pipe and therefore delay the initiation and spread of corrosion. Of the defence mechanisms known to contribute to overall CUI mitigation, it is insulation that is by far the least understood and the least supported by effective and representative testing and assessment methods.

EXISTING METHODS OF ASSESSMENT

// Existing methods for assessing insulation performance against CUI

Many of the test standards employed to assess the behaviour of insulation materials are obscure and considered by many to inaccurately reproduce the type of failure modes that are found in real life situations. The tests, while important, need to be brought into context and interpreted very carefully when decisions are being made about material selection for a particular application or service.

There is a significant amount of detail relating to each of the test methods and as they are well described in literature, they will not be covered here. A summary which includes key features and considerations from the perspective of assessing insulation performance is provided in **Table 1**.

Test Method(s)	Key Features	Remarks
ASTM C871	Measures leachable chlorides and fluorides (+ inhibitors: sodium and silicate)	<ul style="list-style-type: none"> Allows for a basic comparison between material types/ grades. Preparation of the material by grinding may destroy chemical bonds which leads to the measurement of non-leachable ion content Test conditions (high temperature and time) do not reflect actual real-life conditions.
EN 13468	Measures leachable chlorides and fluorides (+ inhibitors: sodium and silicate)	<ul style="list-style-type: none"> Allows for a basic comparison between material types/ grades. Test conditions (high temperature and time) do not reflect actual real-life conditions.
ASTM C795	Determines the acceptable conditions for insulation material to mitigate ESCC based on the balance of corrosion contributors / inhibitors and performance acc. ASTM C692	<ul style="list-style-type: none"> Levels of contributors (chlorides / fluorides) are measured according to ASTM C871 Concentration of inhibitors within insulation may reduce during normal service which is not reflected in the test
ASTM C692	Direct test method to assess the influence of wet insulation material on ESCC for austenitic stainless steel	<ul style="list-style-type: none"> The test method assumes that there is no covering Closed cell or hydrophobic insulation materials are damaged on purpose to allow for a water ingress that would otherwise not normally take place Open cell materials are tested in their actual real-life application condition
ASTM C1617	Measures the mass loss corrosion rate of a chosen substrate through wet/dry cycles with exposure to solution containing leachable ions prepared from the insulation material	<ul style="list-style-type: none"> The solution is normally prepared in accordance with ASTM C871 which involves the process of grinding the insulation material
ASTM G189	Simulation test for the installed insulation system on pipework	<ul style="list-style-type: none"> Water is introduced at the interface between the pipe and the insulation material to simulate a completely compromised insulation The method is designed more to assess the performance of protective coatings The standard is considered a 'guidance'. Pass/ fail criteria is not clear and requires interpretation

Table 1: Summary of existing corrosion test methods applied to insulation materials.

CORROSION UNDER INSULATION ON INDUSTRIAL PIPING

One of the unfortunate aspects about all (or most) of these tests is that they work on the presumption that at least the insulation or covering has failed. While this might be important from the perspective of assessing the performance of certain grades of steel or the applied protective coating, it compromises any CUI mitigation strategy by closing off the opportunity to evaluate the benefits of certain types of insulation material over others.

It is our contention that the only way you can achieve a proper evaluation of materials to combat CUI is to adopt a systems based testing approach^{viii, ix}. Only then can differences between insulation materials that are closed-cell and open-cell, hydrophobic and non-hydrophobic, rigid and flexible, adhered and un-adhered, etc. be truly appreciated and fairly assessed on a comparable, repeatable basis.

ASSESSING THE FAILURE MODE RISK – DEBUNKING THE MYTHS

The idea that a single solution to all CUI challenges exists is completely unrealistic. On the contrary, what the industry is learning about CUI is that it takes a mix of material and covering technologies to address all of the different ways in which CUI can occur. There simply is no single insulation solution that can deal with CUI for all process temperatures, operating conditions, environmental conditions and failure modes experienced.

// Installation and damage failure modes

One of the most important considerations when identifying failure modes for a particular insulation system, is the potential areas of weakness in both design and installation. When it comes to water ingress specifically, understanding the different ways in which materials become damaged is also of critical importance. **Figure 3** highlights some of the key areas of vulnerability in a typical system.

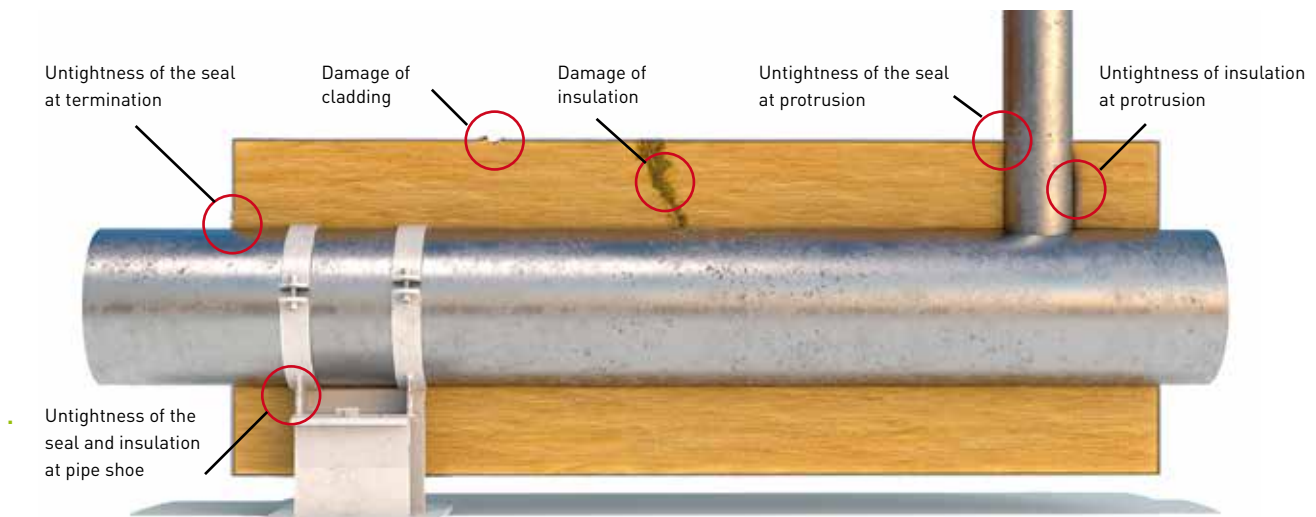


Figure 3: Areas of water ingress vulnerability in a typical insulation system

Mostly encountered failure modes for water or water vapour ingress into the insulation are, e.g:

- Damaged or poor application of external cladding / jacketing
- Damaged or poor application of vapour barrier
- Damaged insulation or poor application of the insulation (particularly at joints and protrusions)
- Poor design (selected insulation system not adequate for the piping and environment)
- Generally poor application and lack of inspection

Water and water vapour ingress occurs in many different ways and some insulation systems are more protective against particular failure modes. However, it is difficult to find a system equally protective for all possibilities. On the contrary, for each insulation system there may be at least one effective failure mode against which the system does not protect.

THE BASIC RISK MATRIX

One way to assess the benefit of an insulation with regards to CUI is to rank its performance against a particular CUI risk. This can be achieved by reviewing the materials behaviour against known standard measurement procedures as well as under tests designed to evaluate specific failure modes.

The starting point on the journey is to describe the specific conditions for a particular CUI challenge which generally depends upon:

- Ambient conditions (high/low or cycling temperature and humidity)
- Process conditions (operating temperature continuous high/low or cycling)
- Failure mode (damaged cladding [and foil], damaged insulation, poor application, poor design, etc.)
- Water phase (liquid or vapour) and ingress path (through cladding, at protrusions, support shoes etc.)
- Water retention

Once these details are known, it is possible to consider how each insulation material performs with respect to each particular failure mode and operating condition. Essentially, in each case we are asking: how well will it restrict (at least for some time) the ingress of water into the system, and how well will it hold water away from the pipe/vessel surface?

By way of example, and looking at this very generally, if we consider a non-hydrophobic and porous insulation material, such as some grades of untreated or uncoated mineral wool, we might argue that such material offers very little protection with regards to liquid water ingress. Closed cell materials (such as cellular glass or FEF), or hydrophobic materials (such as aerogels), on the other hand generally have inherently strong capabilities to restrict liquid water ingress and thereby offer greater protection against CUI. Closed cell and hydrophobic materials therefore score highly with regards to restricting water ingress.

CORROSION UNDER INSULATION ON INDUSTRIAL PIPING

Risk of water / water vapour entry leading to CUI

Water Phase	Operating Temperature	FEF	Aerogel (Flexible)	Aerogel (Less Flexible)	Mineral Wool	PIR/PUR	Cellular Glass
Liquid	High temperature (> 120 °C)	n/a	■ [P1]	■ [P1]	■ [P1]	n/a	■ [P1]
	Med temperature (Amb. to 120 °C)	■ [P1, P2]	■ [P1, P2]	■ [P1, P3]	■ [P1, P3]	■ [P1, P3]	■ [P1, P3]
	Low temperature (< Amb.)	■ [P1, P2]	■ [P1]	■ [P1]	■ [P1]	■ [P1]	■ [P1]
Vapour	Low temperature (-50 °C to Amb.)	■ [P1, P2]	■ [P2]	■ [P2]	■ [P1, P2]	■ [P1, P2]	■ [P1, P2]
	Low temperature (-200 °C to -50 °C)	■ [P1, P2]	■ [P1]	■ [P1]	■ [P1]	■ [P1, P3]	■ [P1]

Risk of water / water vapour retention / spread leading to CUI

Water Phase	Operating Temperature	FEF	Aerogel (Flexible)	Aerogel (Less Flexible)	Mineral Wool	PIR/PUR	Cellular Glass
Liquid and Vapour	High temperature (> 120 °C)	n/a	■ [P1]	■ [P1]	■ [P1]	n/a	■ [P1]
	Med temperature (Amb. to 120 °C)	■ [P1]	■ [P1, P3]	■ [P1, P3]	■ [P1, P3]	■ [P1]	■ [P1]
	Low temperature (< Amb.)	■ [P1, P2]	■ [P1]	■ [P1, P3]	■ [P1]	■ [P1]	■ [P1]

■	Strong performance	[P1]	Proven - Inherent properties - WVT, water absorption, etc
■	Moderate performance	[P2]	Proven - Armacell testing - eg. TNO, INNCOA, CINI tests etc
■	Low performance	[P3]	Proven - Independent testing - eg. Shell, NACE, site trials etc.

Table 2: Risk matrix of insulation material performance against specific conditions that govern CUI (excluding outer covering or vapour barriers).

This argument can be counter-balanced for example in the event that water does get into the system as a result of installation errors, the water will find it harder to escape from the system constructed from materials with closed cells as compared to materials with porous structures.

By recognising and accepting some of these fundamentals taking this approach enables us to summarise the performance of different insulation materials for specific conditions that increase the risk. **Table 2** presents the behaviour of commonly applied insulation materials (stand alone, without vapour barrier foil and without covering) and maps their performance against CUI risk as a function of service temperature, water phase, and for both water ingress and water retention behaviours. The performance is ranked with strong, moderate and weak performance which has been determined through assessment of available test results.

The approach described here is simplified. The topic of materials performance is more complex than presented here and each material manufacturer will understandably argue from their own perceived positions of strengths and weaknesses that this is highly nuanced and there are many details that need to be considered. For example, it considers the inherent properties of the insulation materials and does not consider opportunities to combine with other materials, e.g. vapour barriers etc.

INSULATION MATERIALS AND SYSTEMS

While the table does present a simplified view, we are seeking to encourage insulation and coating engineers to think differently about their own approach to insulation design and CUI mitigation, recognising first and foremost that different insulation materials perform differently and that there is no 'one stop' solution for CUI mitigation in all circumstances.

We see from the above that there are three key areas relating to CUI where the behaviour of the insulation material plays a significant role. Specifically this is a) water ingress, b) water spread and c) water retention. These will be discussed in the sections below:

// Reducing water ingress

As described earlier, the ability of an insulation material to reduce water ingress is especially important. Closed cell materials, such as Flexible Elastomeric Foam (FEF) and cellular glass, or hydrophobic materials, such as aerogels and some mineral wool grades, offer high resistance to the ingress of water in liquid phase. For water vapour, closed materials offer the highest level of protection, a feature that has long been recognised by some of the world's leading authorities on corrosion*.

Material with fibrous and open cell structure

1. Protection from external water vapour provided solely by metal jacketing
2. Damage of metal jacketing
3. Water spray & moisture penetrating the material
4. Galvanic corrosion of metal jacketing
5. Wicking of the insulation material occurs

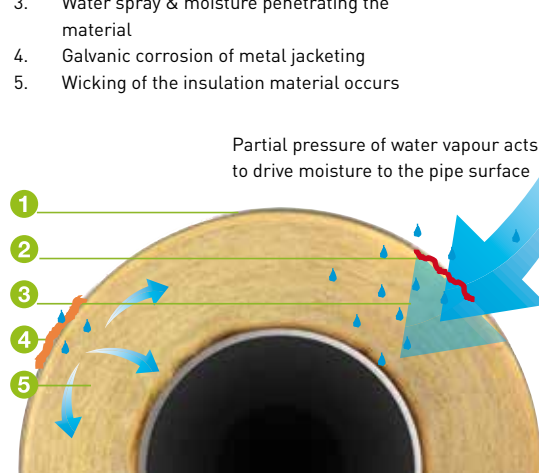


Figure 4. Materials with open cell or porous structures are dependent on the external vapour barrier for concentrated diffusion resistance.

Elastomeric material with closed cell structure

1. Protection from external water vapour provided with the structure of FEF material
2. Distributed diffusion resistance with closed cell structure

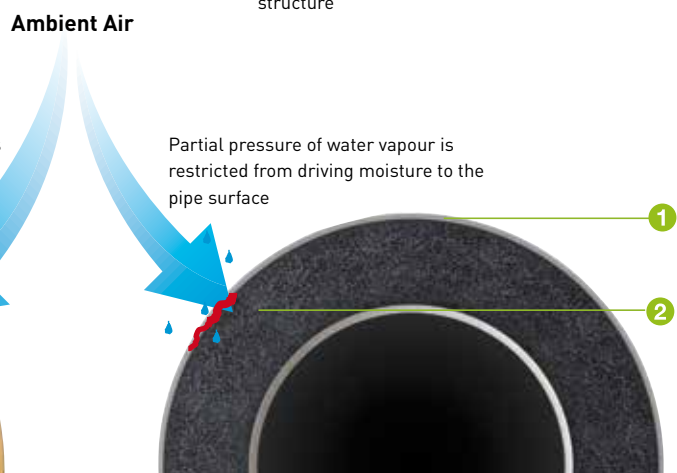


Figure 5. Materials with closed cell structure offer built in defence against water and water vapour ingress.

Open-cell or porous insulation materials that are not inherently hydrophobic are susceptible to liquid water or water vapour penetration if the external jacketing and/or vapour barrier is compromised. As water enters open cell or porous insulation materials, water can penetrate into the insulation layer by way of capillary action (or wicking). **Figure 4** and **Figure 5** illustrate the features of open cell or porous insulation materials, such as mineral fibre (Figure 4), compared to closed cell insulation materials, such as FEF (Figure 5).

CORROSION UNDER INSULATION ON INDUSTRIAL PIPING

// Reducing water retention

While closed cell and hydrophobic materials offer good resistance to water ingress, many of these materials are also good at retaining water which, if left alone, will lead to CUI over the longer term. This is especially true if the ingress path is left untreated and water continues to “fill” within the system.

In the case of porous hydrophobic materials applied in high temperature service, water is able to readily escape by means of evaporation through the breathable insulation layer. For low or moderate temperatures (say < 80 °C) evaporation rates are lower and additional steps need to be taken to ensure that any water retained within the system can escape. e.g. by the introduction of drain holes in the covering layer.

In the case of cold or cryogenic insulation, there exists the additional challenge of removing water which has collected as a result of water vapour ingress. Here the use of drain holes are undesirable since they allow for water vapour to enter the system. For cold/cryogenic systems the focus once again turns to material technologies and combined technologies (such as vapour barriers) that limit ingress of water in vapour form.

// The annular space

The annular space that develops between the insulation and the pipe surface is very often overlooked. Annular spaces create a collection point for water when it becomes trapped within the system. Although not exclusively so, annular spaces are generally a problem with rigid insulation materials regardless of whether the material is open or closed cell (e.g. cellular glass, PUR and mineral wool sections). ASTM C585^{xi} is often used to control the size of voids for rigid insulation but even when these tolerances are followed, water will always not readily drain away because of the ‘meniscus effect’ which acts to retain water against the pipe. Flexible insulation, such as aerogels and FEF, on the other hand, are usually designed to have a much closer fit to the pipe across the entire surface and this reduces the possibility for annular spaces to exist.

The degree of flexibility is also an important factor which determines the likelihood that annular spaces or voids will develop between the insulation and the pipe. Recent work performed by InnCoa shows that an aerogel blanket with greater flexibility has a better ‘fit’ against the pipe surface thereby reducing the chance that water can collect. Less flexible aerogel blankets lead to wrinkles and creases being introduced between the pipe surface and material layer which creates localised corrosion where the spaces are formed.

Finally, in the case of flexible closed cell insulation materials (such as FEF), the material is either preformed or shaped to accommodate exact pipe dimensions and may be adhered directly to the pipe or vessel surface. These application techniques ensures that the annular space is effectively eliminated.

// Reducing the spread of water

As described above, open cell or porous insulation materials will facilitate the spread of water through a process of wicking. Here, water will spread to any part of the insulation system, including areas upstream and downstream of the compromised section so long as there is continuity of layering. Eventually, if the failure point is left untreated, a continuous supply of water into the system will result in the materials becoming completely saturated with moisture.

CORROSION UNDER INSULATION ON INDUSTRIAL PIPING

While the inherent capabilities of the insulation for reducing water ingress are important, another consideration for reducing the spread of water within the system is how the insulation materials are fixed in position and how their joints are sealed. Generally, open cell materials are held in position by way of a mechanical fixing and joints are rarely sealed. The material is dependent upon a tight fit to ensure continuity of performance (such as hydrophobic properties) at the joint detail. For other insulation types, while fixing methods can vary, the joints are invariably sealed either with a proprietary adhesive or a mastic/caulk sealant.

For rigid insulation, the mastic/caulk is commonly used to fill the gaps between the sections of insulation. The mastic/caulk does not provide the same thermal properties as the insulation itself but it can provide an effective seal against water ingress. Ensuring all gaps between insulation sections have been suitably filled is especially important at these vulnerable areas in order to reduce the possibility of water ingress between adjacent sections and layers. In the case of closed cell FEF insulation materials, compatible contact adhesives coupled with compression fitting enable the insulation sections to be joined without any gaps at all. This effectively creates a seamless and continuous insulation layer where continuity of performance is maintained throughout the system.

Regardless of the insulation selected, it is always necessary to ensure that multi-layers are overlapped with staggering both at circumferential and longitudinal joint areas. This ensures that there is a tortuous path for water to travel which reduces the chance of water penetration to the pipe surface.

// External coverings and vapour barriers

In addition to the mechanical and environmental protection it provides to the insulation, the external jacketing or cladding material is the first lines of defence against water ingress. For the oil and gas sector, it is common place to see the following material types employed as a covering system over the insulation materials:

- Metal jacket (galvanized steel, stainless steel, aluzinc, aluminized steel, aluminium)
- UV-cured, rigid GRP cladding (Glass-Reinforced Plastic) known also as fibre-reinforced plastic (FRP) in the USA
- Flexible elastomeric covering (with or without integrated reinforcing fibre-glass scrim)
- In-situ applied coatings with in-built textile or fibre-glass scrim
- In-situ applied mastics

The choice of covering material will usually be selected on the basis of its fire performance, mechanical/physical properties, and most importantly, its compatibility with the underlying insulation itself. For example, rigid claddings like metal jackets or GRP are normally applied over mineral wool, aerogel or other forms of mineral/glass fibre insulation blankets. Flexible elastomeric coverings are normally applied on FEF (Flexible Elastomeric Foam) insulation. In-situ applied coatings and mastics are normally used on rigid insulation materials like cellular glass. In every case the selected and specified type of cladding should match the selected and specified type of the insulation material and manufacturer's instruction should be followed at all times.

CORROSION UNDER INSULATION ON INDUSTRIAL PIPING

Rigid claddings, as well as semi-rigid in-situ applied coatings with scrim reinforcement, are potentially vulnerable to thermal expansion and contraction due to daily and seasonal ambient temperature amplitudes. Longitudinal contraction can potentially occur with mastic coatings leading to the possibility of pulling away at terminations and protrusions. Flexible elastomeric coverings do not suffer from these effects but as with rigid insulation coverings, they are nonetheless dependent upon the quality of the seal being applied.

Similarly, the insulation may expand and contract as a result of process temperature, especially when cycling. Once again, it is important that due consideration is given to the compatibility of the chosen insulation and covering layer. For rigid covering materials, it is possible that either as a result of cycling temperatures, or simply over time, the covering no longer fits tightly around the insulation system. In such cases, a space between the insulation and the covering may appear and this may become a collection zone for water.

For cold or cryogenic insulation systems, it is sometimes good practise to install additional vapour barriers (such as metallic foils) to protect the insulation against water vapour transmission. This is especially necessary for insulation materials having low water vapour transmission resistance which will absorb moisture over time. Despite the best efforts of the installer, it is not uncommon for these vapour barriers to be damaged during their application or for deficiencies in their sealing to occur. Even defects as small as a pin hole in the barrier can lead to a continuous diffusion of water vapour into the system which results from the difference in the partial pressure developed between the ambient and pipe operating temperatures.

In some cases, where there is a concern about the integrity of the vapour barrier, a sacrificial layer of insulation may be applied to separate the vapour barrier from the covering. Closed cell FEF materials lend themselves well to this particular requirement as they have an integral vapour barrier running through the full thickness of the layer. The installation of a 13mm (1/2") or 19mm (3/4") thickness will shield the vapour barrier from incidental damage and provide protection when, for example, screws and rivets are used to secure metal jacketing in place.

// Fixings and attachments

API^{vi}, NACE^{iv} and CINI^v identify areas that are particularly vulnerable to water ingress and therefore require special attention during construction. These include:

- Protrusions of all kinds, (e.g. valves, lifting lugs, platform and stair brackets, ladder supports, skirts, insulation support rings, nozzles and manways, protruding instruments etc.)
- Pipe supports (e.g. pipe shoes, metal clamps, insulated cryogenic etc)
- Terminations, reductions, dead-legs

Figure 6 and **Figure 7** are extracted from NACE SP0198^{iv} and from CINI Manual, section 1.2.04^v documents, respectively, and highlight the areas which are most susceptible to water ingress on vessels and process pipework.

Closed cell, flexible insulation materials offer considerable advantages over porous or rigid insulation because they can be installed with compression around the protruding parts or complex shapes ensuring a vapour tight seal is achieved. Rigid insulation is highly dependent upon the correct application of sealants and caulks while the external vapour barrier provides the only line of defence for porous insulation materials. In the latter case, many challenges exist in ensuring a vapour tight seal.

CORROSION UNDER INSULATION ON INDUSTRIAL PIPING

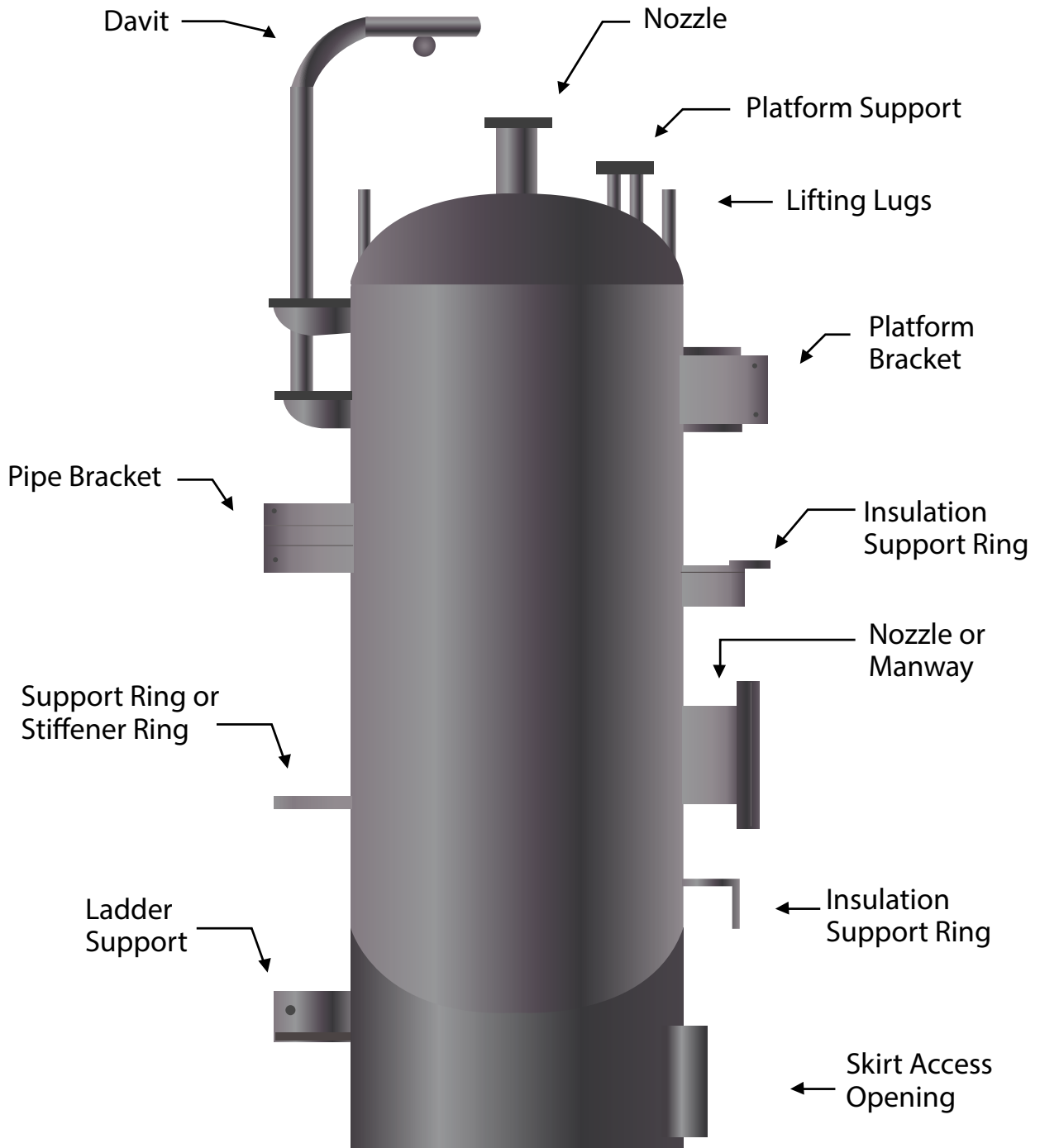


Figure 6: Typical locations particularly vulnerable to water ingress (vessel)^{xii}.

CORROSION UNDER INSULATION ON INDUSTRIAL PIPING

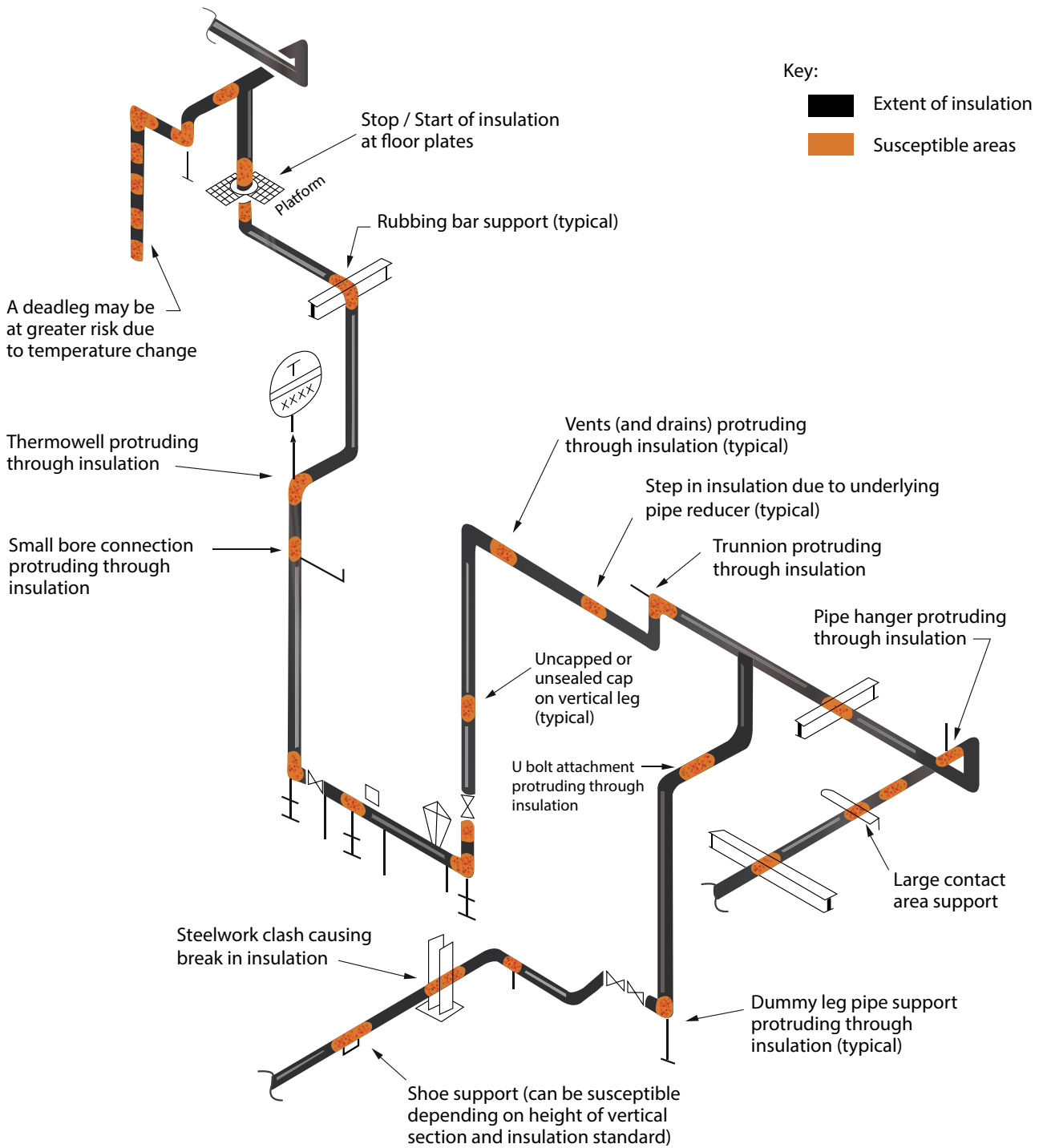


Figure 7: Typical locations particularly vulnerable to water ingress (industrial piping)^{xiii}.

// Materials application

Of critical importance for any insulation system is how it is installed. Systems can be designed to provide multiple levels of defence against CUI, but it is always important to ensure that due care and attention is given to their installation and upkeep during their service.

// Installation instructions

As a general rule, installers should always follow the application instructions and guidance provided by the relevant manufacturer. In many cases, especially for complex multi-layered insulation systems, this will require following separate procedures for each material component (e.g. coating, insulation, acoustic barriers, vapour barriers, jacketing etc.).

It can be expected that application instructions will usually address typical details such as straight horizontal pipework or vessels. Although this may cover the majority of pipework installed on a project, these are not always the locations where the greatest risk occurs. Generally it can be assumed that anywhere where there is a break in the continuity of the system will there be an 'invitation' for water to ingress and manufacturers should offer guidance on how to deal with these vulnerable areas.

Wherever instructions are not readily available, materials manufacturers should work together with the relevant contractors to ensure that detailed instructions and drawings are created to address these specific areas. This should be agreed between the project partners before any work on installation begins. In certain cases, it may be considered appropriate for a system mock-up to be created in order for all concerned parties to verify the proposed solutions and agree on necessary construction details.

// Workmanship and training

Consideration must be made in relation to the skill set of the material installer. A failure to use persons trained to apply insulation materials will lead to a significant risk that application instructions will not be followed and that the system installation is compromised in some way.

In many cases, installers will require additional training in order to ensure that they become familiar with the particular material technologies being used on a given project. It is no less reasonable to expect that insulation materials are treated in same way as protective coatings by ensuring that necessary preparations are made for the insulation to be applied as intended by the manufacturer. It is especially important to maintain these standards even when project delays and time pressures.

There is slowly becoming a recognition by some of the oil and gas majors that this way of working can no longer continue and that training and, where necessary, site support be a mandatory requirement. As a result the requirement for contractors to implement training is being introduced into new project insulation specifications more and more. This dramatically increases the level of confidence that the insulation system has been installed correctly.

CORROSION UNDER INSULATION ON INDUSTRIAL PIPING

// Inspection and maintenance

A key feature of any good inspection and maintenance programme is that it is designed to target the specific areas that are most vulnerable to CUI and to ensure that steps are taken to rectify any identified issue long before it becomes a much larger problem. Having an understanding of the key properties and features of the specific insulation materials and coverings being applied, and understanding which areas are most susceptible to water ingress and CUI, will better equip facility owners to build inspection and maintenance programmes that deliver longer asset life with less operation interruptions.

Inspection begins during the construction phase and is usually conducted according to dedicated Inspection and Test Plans (ITP's) which have been developed for the particular material and system being installed. ITP's are generally created by the contractor with the support of the insulation manufacturer. It is important that the inspection teams develop confidence that the materials are being installed as they were designed to do and that issues such as water ingress taking place during construction (e.g. through rain or deluge testing) are dealt with in full.

Once the systems are completed, it is important to ensure that regular and routine inspection and maintenance is carried out. This should start as soon as the insulation has been completed, not just when in service, especially if there is a long delay between the installation and plant start-up. General considerations for a basic visual inspection may include:

- Condition of jacket, joints
- Perforations, gaps, dents
- Crushed insulation (reduced thickness)
- Evidence of ice, condensation, etc
- Evidence of overheating
- Insulation removed but not reinstated

It is common for walk around visual inspections to occur weekly or monthly, depending on the size of plant and the particular process /operating frequencies that are involved. While non-invasive technologies do exist to assess water ingress / CUI (such as: Infrared, microwave and ultrasound techniques), it will sometimes be necessary to make invasive inspections into the insulation which may occur as a result of a concern about a particular location, or as a yearly planned programme of limited spot checks of removal/reinstatement. The periods between strip/reinstatement will be based on client confidence, maintenance plan and legal or Health, Safety and Environment (HSE) requirements.

For most insulation materials, the process of removal and replacement is cumbersome and often involves the removal of large quantities of material, even if the intention is to address one particular location. The benefit of FEF insulation materials is that they make it straight forward for inspection and maintenance to take place through the removal only of materials that are related to the affected area. Considering that FEF materials dramatically restrict the spread of water and corrosion following a breach in the system, the benefit of being able to target and address very specific areas on the installation offers a huge cost and time benefit to the inspection and maintenance teams. This is in stark contrast to many porous and non-hydrophobic insulation

CORROSION UNDER INSULATION ON INDUSTRIAL PIPING

systems where a breach in the covering or vapour barrier often leads to CUI which can spread significant distances along the pipe both upstream and downstream from where the breach occurred.

Figure 8 shows an example of an inspection 'port hole' created with an FEF insulation system to demonstrate the ease with which material can be removed and replaced at a specific location.



Figure 8. Example of inspection 'port hole' created with FEF insulation materials.

Additional features and benefits of closed cell FEF and also hydrophobic insulation materials that aid inspection and maintenance activities include:

- Water penetrating through the cladding will not be readily absorbed by the insulation and is often limited to the area between the cladding and insulation
- Water ingress is observable – especially when used in combination with elastomeric coverings
- Water will not gather in the annular space between the insulation and the pipe (because of all-over-adhesion or tight-fitting)
- Water will not condense on the inner surface of the covering (because of all-over-adhesion and/or lack of air gap)
- Tightly installed, compression fit will help to maintain water tightness at joint details and protrusions/ terminations

CONCLUSIONS AND RECOMMENDATIONS

It is becoming increasingly recognised that the type and design of insulation materials plays a much more important role in the fight against CUI. Existing standard methods used to evaluate the performance of insulation materials offer a limited perspective on their ability to mitigate corrosion and alternative system tests are recommended.

The paper looks in detail at the influencing factors of moisture, temperature and leachable ions on CUI and introduces the reader to the concept of a failure mode assessment. It describes a process for mapping out material performance characteristics against specific failure mode categories (i.e. operating temperature, water/vapour phase, water ingress/retention etc.). Recognising that there is no single solution for CUI, and that it takes different materials and combinations of materials to address different CUI scenarios, it presents the case for a systems based approach to testing.

The paper considers some of the features and benefits associated with Flexible Elastomeric Foam (FEF) and aerogel materials and discusses some of the characteristics of closed-cell structures, compression fitting, all over adhesive coverage, hydrophobicity and reduction in annular space, all of which act to reduce the spread of CUI which is especially important on termination areas, pipe supports or where protrusions may occur.

Some of the characteristics found in Flexible Elastomeric Foam (FEF) and aerogel materials, such as closed-cell structures, compression fitting, all over adhesive coverage, hydrophobicity or reduction in annular space, all act to reduce the spread of CUI.

It is hoped that the general approach proposed in this paper will enable the reader to improve their knowledge of insulation materials and their influence on CUI risk and furthermore, be able to make informed choices about material selection and better identify vulnerable areas on the facility where CUI is likely to occur, thereby allowing appropriate CUI management strategies to be adopted.

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