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Abstract

Corrosion Under Insulation (CUI) continues to be an issue in many oil, gas and petrochemical installations. This paper builds on previous work to examine why the industry has struggled to come up with reliable and cost-effective solutions to the CUI problem. The limitations of different multidiscipline innovations are discussed together with positive examples of the latest promising industry projects and research, including risk management guidance, improved coatings, insulation system materials and design, non-destructive screening techniques and permanently embedded monitors. Key learnings from this review demonstrate the importance of better use of industry plant data to achieve improvements in managing CUI in all innovation disciplines.

1. Introduction

One would think that improvements in the management of CUI would be significantly enhanced by a combination of better prediction techniques, application of more robust insulation system barriers, and use of reliable inspection techniques. However, the reality is that after more than 20 years of innovation in these areas it is apparent that predicting or proving what works is surprisingly difficult.

Periodic inspection is still the best way to prevent CUI failures, but it is both expensive and resource intensive. The success of any new CUI solution or technology relies on confidence in performance to enable operators to relax inspection or justify additional value by reducing failures (Figure 1). The consequence of a failure of extremely critical equipment be too significant to rely on assumptions.

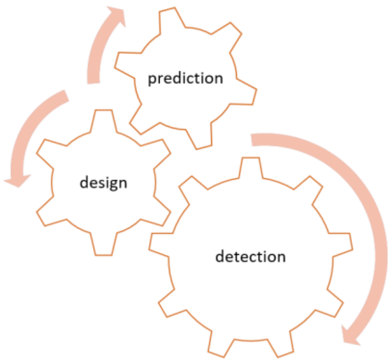

Figure 1. Prediction of performance is a key multidiscipline part of CUI innovation.

The capture and sharing of CUI data from operating plants plays a key role in addressing this issue because the many different combinations of geometry, environment, barrier materials and ageing mechanisms in operating plants provide the most sound and comprehensive basis for assessment that is hard to model from short-term simple laboratory test setups.

Although we owe most of our CUI knowledge to field experience, this is also a problem because data are not widely shared, and it can take over 20 years to collect meaningful data. This paper illustrates the important role of the operator in sharing historical plant data and facilitating field trials. Examples of useful plant data are provided including observations from an overview of 13 recent significant CUI occurrences and failures. Key limitations of different CUI solutions and technologies are discussed, and examples are shared of the current industry responses that tackle how to resolve uncertainty in performance and establish confidence in the performance of innovations over shorter time periods.

2. Importance of sharing data

Experience with CUI in operating plants is important because it provides realistic data for the many factors that are influential in causing CUI in practice and are not easy to replicate in the laboratory. For instance, a wide range of damage severity is observed for all types of equipment geometries even for equipment operating at the same temperature, or which there is no simple explanation that can be obtained from testing to apply in the field. The same is true for coating life which cannot yet be reliably extrapolated from laboratory testing. Experience obtained from operating plants can include failures and anomalies cross-referenced with time and other easily measurable factors. This shows that it can take 15 to 20 or more years of field exposure to provide information to prove the success of any design, prediction, or detection solution.

Recent work [Watt, 2019] has revealed that only a handful of CUI datasets [Kurihara 2010, Tateno 2012 and Burhani 2019] from operating plants provide the basic knowledge that is used for the various CUI prediction techniques applied by many operators in the oil and gas industry. This underlined the need for more sharing of CUI data within the industry. The work [Watt, 2019] also provided a new dataset for CUI in an onshore plant in a marine environment and challenged key assumptions in the various industry guidance documents concerning influential factors and inspection coverage requirements.

Significant CUI can often be extremely isolated and may not be picked up by low coverage inspections. Reliable conventional CUI management schemes with conservative inspection intervals and 100% insulation removal for extremely critical equipment are often successful and there is evidence this usually justifies the investment for typical oil and gas installations. Preventing just 2 or 3 critical failures would likely fund 30 years of reliable CUI inspection schemes, these schemes typically costing ~£0.5-1 M/year and deployed after 10 years of service.

So why don’t all operators implement reliable insulation removal and inspection schemes? Perhaps in part, because the published guidance does not provide a consistent approach, perhaps also due to the variable frequency of occurrence of CUI in plants, either early or late life. It can take a long time to prove a CUI management strategy as ineffective.

There are many examples where the knowledge to prevent significant CUI failures was pre-existing. In the example below in Figure 2, had the operator of Plant A known about previous experience with CUI at column support rings shown in Plant B, it is likely that an appropriate inspection program would have been put in place to catch such degradation before the failure occurred. Experience from many plants has shown that support rings drive considerably earlier metal loss by CUI than the rest of the equipment.

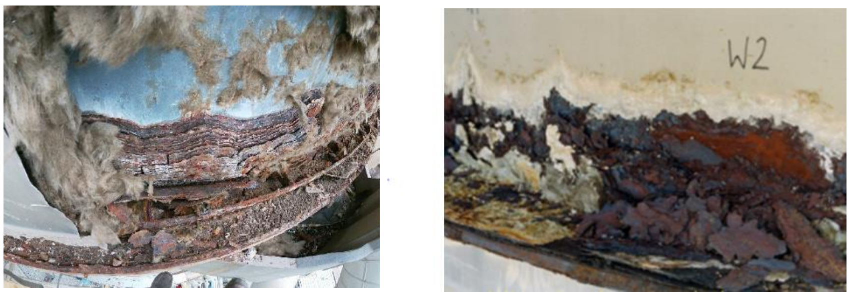

Figure 2, CUI of column support/stiffener rings to CUI
Plant A (left) through-wall leak 2020 age 20 years. Plant B (right) severe CUI 1999 age 5 years.

Figure 3 shows recent examples of CUI failures that would have been prevented had a reliable insulation removal and inspection scheme been applied in the respective plant.

Figure 3. Examples of preventable serious failures if reliable inspection schemes had been used.

Around a half of the failures or significant CUI occurrences reviewed for this paper might not have been captured in time by reliable inspection schemes (in a temperate/marine climate) and these all relate to design factors, e.g. vessel support rings, but also included are coating/insulation systems that are widely considered to delay the onset of or reduce the severity of CUI. Two such examples (Figure 4) involving different plants are related to the use of adhesives where closed cell insulation was applied to equipment operating at temperatures above ambient. These issues occurred 14 years ago, yet the experience is still not included in published in-house or design guidance. Even if such failures are rare, they could drive unnecessarily conservative inspection strategies if the experience is applied needlessly to equipment for which they are not relevant.

Figure 4. Examples of early severe CUI (>10mm loss in 6-10 yrs) in unusual locations associated with use of adhesive with closed cell insulation for equipment operating at elevated temperature.

Improved sharing of data and appropriate follow up analysis applied in a consistent and structured manner could help identify unique combinations of factors that lead to severe or early CUI failures. This could make it possible to take steps to avoid such combinations and to optimise inspection strategies for the remaining equipment. Traditionally operators have been reluctant to share CUI experiences and data, particularly where there is a perception that such openness could have reputational consequences. Anonymising information can help in this respect. It is often the case that real gems of information from experience in operating plants are diluted when captured in guidance documents, perhaps to avoid being too prescriptive. Availability of the raw data would enable people to make their own and possibly more applicable assessments rather than relying solely on the guidance.

There is a need for an open platform for sharing CUI experience and data to improve judgement in predicting risk of CUI and identifying cost effective actions to reduce CUI. It is surprising that no joint industry initiative exists, although there are planned commercial initiatives to attract data to commercial databases or software solutions and apply data analytics for the benefit of all users.
Pulling key CUI information together in a structured manner has been attempted with the recently published DNVGL RP-G109 [2019] document. This is certainly a step in the right direction and provides open access to a simple risk-based assessment methodology. It has a number of advantages over other guidance documents but, in common with them, is still limited by lack of sharing of CUI data, especially in terms of factors which can lead to underperformance of some design solutions (as discussed in this paper).
The use of so-called digital twins is another approach to improve the way in which CUI data can be utilized more effectively. Digital twins are scanned and digitized models of operating plant that enable detailed desktop visualisation with ability to link up with process instrumentation and design data. Some operators are planning to or have invested in these models. This is likely to help implement CUI management strategies in a more structured way and enable plant process profiles to be better understood, as well as targeting appropriate deployment of different innovations or inspection techniques.

3. Limitations of CUI innovations

As discussed above, reliable periodic insulation removal and inspection can prevent many serious CUI events, but is intrusive, labour intensive and expensive, driven by short intervals and high inspection coverage. Inspection was never intended to be a primary corrosion control technique.
In adopting any new technology to achieve a step change in effectiveness of CUI management, operators need assurance that the technology is reliable, efficient, and cost effective. Current innovations proposed for CUI suffer from limitations ranging from uncertainty in performance to restrictions in application. These limitations have been categorised as follow:

A. Not widely deployed
B. Deployed for long enough, but not enough field performance data shared
C. Not cheaper/quicker to deploy than traditional approaches
D. Application limits (cannot be used for all equipment) generates additional planning complexity
E. Uncertainty in reliability, either due to lack of supporting field data, limitations around the representative nature of testing, or reported adverse field experience that is not fully understood and needing more fundamental investigation.
F. HSE concerns associated with working with the technology

Table 1 provides an overview of which of these limitations apply to common CUI innovations currently on the market. Some of these innovations may yet prove to be highly effective and there are a number of currently funded projects, although not all in the public domain, that aim to better predict reliable performance in the field, some of which are discussed below in more detail.

Technology categories	***A. Not widely deployed***	***B. Deployed ≥ 15-20yrs no data share***	***C. Not generally cheaper than traditional approaches***	***D. Application limits/added complexity***	***E. Reliability uncertainty / fundamentals not widely understood***	***F. Safety when using***
Coatings that could extend life						
TSA coatings		*X*		*X*	*X*	*X*
Immersion coatings		*X*			*X*	
Intelligent coatings self-healing/sensing	*X*					
Insulation system designs that could extend life						
Closed cell insulation @ higher temperatures	*X*	*X*		*X*	*X*	
Aerogel insulation	*X*	*X*			*X*	*X*
Drainage holes	*X*				*X*	
Use of spacers	*X*			*X*	*X*	
Non-metallic cladding		*X*			*X*	
CUI direct screening inspection or permanent monitoring						
PEC	*X*		*X*	*X*	*X*	
RTR (faster e.g. OpenVision)	*X*		*X*	*X*	*X*	*X*
TAXI	*X*		*X*	*X*		
Capacitive sensors (wall loss/ water)	*X*				*X*	
CUI indirect screening inspection or permanent monitoring						
Thermography	*X*			*X*	*X*	
Humidity sensors cladding inserts	*X*				*X*	
Sensors @ metal surface (water/coupon)	*X*				*X*	
Sensors @ metal surface (water)	*X*				*X*	

Table 1. Summarising key issues that limit the use of common CUI innovation technologies. Note empty boxes indicate no information or not applicable.

Coatings

Many coating systems are available for carbon/low alloy steels and stainless steels, with different performance and application specifications. As a barrier to CUI, three generic coating types are commonly distinguished in order of general performance:

- Thermal Spray Aluminium (TSA)
- Immersion grade
- Conventional

At present, there are no published long-term plant data relating to the performance of immersion-grade or TSA coatings applied under insulation. TSA has been generally considered to be the industry 'Best Practice' but there are reports of mixed experiences. Currently, the only tools that coatings manufacturers and operators alike have for qualifying coatings for CUI service are laboratory-based tests, i.e. ISO19277 [2018], which includes both dry and wet test methods, but these typically are short (6 weeks) duration. The problem is that current test methods actually used by the industry are different and hinder comparison, and the results are not easily extrapolated to represent long term field performance, i.e. a lack of correlation with field experience [Daly, 2017].

Over the past few years several industry joint initiatives have been actively pursuing improvements in these areas. NACE (now AMPP) set up Task Group TG516 in 2015 to assess all currently published CUI test methods and to develop a new standard to prequalify coatings (both TSA and non-metallic) for use under insulation. Key inputs will include the results from a joint industry project executed by SwRI (Texas), funded by operators and coating suppliers, as well as the test results obtained from the commercialization of the SwRI test method developed. The SwRI work compares both TSA and non-metallic coatings.

NORSOK M501[2012] is currently being revised to include coatings other than TSA for use under insulation, to align more in this respect with NACE SP0198 [2016]. This is also reflected in IOGP S715 [2020] draft Supplementary Specification to NORSOK M501 [2012]. Currently, IOGP S715 [2020] references ISO19277 [2018] as the preferred CUI test standard but very soon there should be a kick-off of a revision to the ISO standard to include the TG516 methodology.

Other significant questions remain for coatings such as; whether they can achieve equal performance when repaired in less-than-ideal field conditions, whether some are more vulnerable to application error and whether some have aged even when they visually appear undamaged.

Thermal Sprayed Aluminium (TSA)

TSA has been advocated in industry guidance, eg. EFC55 [2015], NORSOK M501[2012] and by some operator in-house specifications as the preferred coating under insulation. It has been deployed widely for 15-20 years and so there should be meaningful field performance data available, but unless these are published it is difficult to understand the background to the anecdotal evidence (both positive and negative) that often abounds in the industry. Many current guidance documents take credit in CUI risk assessment for TSA coatings, but early TSA coating failures and severe CUI have been experienced over the past decade. It is unclear whether these are all associated with specification/application errors or influenced by service conditions, but it is clear that failures can occur once equipment is in service. Figure 5 illustrates TSA degradation after 17 years in service on an offshore insulated vessel at 100°C. More rapid degradation has been observed in a recent example in which almost 90% wall loss occurred after 10 years' service with an offshore TSA coated pipe under jacketing operating at ~85°C.

Figure 5. Example of TSA coating degradation under insulation after 17 years at 100°C

One concern uniquely associated with TSA relates to where local conditions can accelerate CUI due to thin liquid films trapped at the metal surface promoting accumulation of aluminium chlorides which cause localized acidification. This mechanism was discussed in a SINTEF report [2010]. It is known that these conditions can be produced by the application of conventional coatings over TSA (i.e. a duplex system) instead of a thin seal coating, and under neoprene riser wraps where the seals failed and allowed water ingress. Over-coating or seal coating is no longer considered necessary by many operators. There may be other examples that have not yet been reported.

One advantage of TSA is that unlike conventional coatings, it may be easier to extrapolate laboratory test data for TSA degradation rates to a "field life" due to measurement of metal consumption. In addition to the work being conducted by SwRI, TWI has also been investigating the performance of TSA under insulation for an international operator.

The authors are not aware of any reported issues with CUI and TSA relating to lower temperature applications. TSA may prove to be highly effective at these temperatures, i.e. combating early CUI in sweating situations, a common problem in hot humid climates for example with cryogenic equipment deadlegs and heat sinks.

In practical terms, field application of TSA requires safety management, and many operators are cautious. Hot work procedures often require habitats which, as a confined space, require regular gas checks, heat fatigue safety checks and control of carbon monoxide build up. Some operators have successfully applied TSA live to large vessels. In terms of piping, there are some examples of field application conducted successfully without the use of habitats in hot humid and temperate climates.

"Immersion" coatings

"Immersion coatings" are believed to have been in service for around 15 years and are defined as qualified for extreme exposure (CX/IM4) or in accordance with IM4 [ISO 12944-2, 2017] (even though there is no CP for insulated systems). Testing would be as per ISO 12944-9 [2018] which includes the requirement for a seawater immersion test.

In recent years, it has been recognized that generic coating system types, (e.g. epoxy phenolic, epoxy novolac or inorganic co-polymer matrix coatings), do not sufficiently describe the performance of different formulations within these categories and the industry has moved towards performance-based selection.

Intelligent coatings

Intelligent coatings e.g. self-healing/sensing coatings have only recently been commercialised and therefore there has been little deployment, so experience is needed. There are some ongoing studies by operators with atmospheric exposure because performance is easier to evaluate.

Insulation system designs

Closed cell insulation at higher temperatures has had relatively limited deployment over the last 15-20 years as a design solution or as an upgrade for older equipment to help combat CUI. It has been available for 40 years and was initially used at low temperatures, but CUI has still been reported under ambient/0°C conditions, for instance 50% wall loss of high-pressure cryogenic vessel bridle piping after 15 years' service. The use of adhesives to bond closed cell insulation to vessels that operate at elevated temperature has been linked to severe CUI at unexpected locations. Adhesives are extensively used for low temperature application with no reported issues. Overall, there are a lack of published data including any testing.

Aerogel insulation has been available for 15-20 years but has had limited deployment in operating plant and the experience has not been generally shared. Aerogel products have hydrophobic properties and can allow vapour to escape the insulated system. In terms of safety, there have been concerns with dust and nano-particulates exposure.

Drainage holes/systems have long been advocated for hot insulation designs if oriented correctly and close enough together, (e.g. CINI Manual [2020] or DIN4140 [2014]), but have had limited deployment. It is known that a Norwegian operator has deployed this solution for more than 15 years, but there are no published data regarding key details such as inventory size, type and inspection method used to demonstrate positive performance. Drainage may not work for all geometries or designs. Fundamentals such as movement of water and capillary action are not fully understood, such that it is unclear whether drain holes could promote wetting or decrease severity of CUI by preventing water pooling or assisting dryout with ventilation. Drain holes may also suffer from blockages if not properly maintained.

Spacers (distance insulation or distance cladding) are water management products that minimise contact between water and insulation or hold the insulation away from the metal surface. These are often recommended in conjunction with drain holes. Similar comments apply as for drain holes. There is a lack of published experience data with these systems, but they may be a good solution. However, they add cost and complexity by increasing the outside diameter and may not work for all geometries. For low temperature applications distance insulation should not be specified, but distance cladding can be used.

Non-metallic claddings have been widely deployed over the past 15-20 years. There are various types. They may create a more water-tight system than metallic cladding, but the sealed butt joints and terminations are not vapour tight and as all these types of cladding have similar sealing technologies, they can promote water accumulation via vapour ingress and condensation, the water then being trapped and unable to escape. Several UK operators have experienced that drainage is especially important for certain types of flexible non-metallic cladding. One system is now supplied with advice to install correctly oriented drain holes for equipment operating at elevated temperature. However, not all suppliers make this requirement clear, and not all operators have implemented the advice. This critical design requirement is especially important for non-metallic flexible claddings and this is not sufficiently emphasized in published guidance. Figure 6 demonstrates how large quantities of water can accumulate over short periods. This effect has been observed in temperate hot and colder climates but has been little explored in laboratory tests. The concern is that severe CUI could occur without tell-tale bulging. One asset recently experienced a severe CUI issue for pipe with a non-metallic flexible cladding without drain holes (with closed cell insulation and TSA coating). On the other hand, there are some more recent examples of adoption of drain holes with this type of cladding. Overall, it is still unclear how non-metallic claddings (installed with drain holes) compare with conventional metal clad systems.

Figure 6. Tell-tale signs of bulging in a flexible non-metallic product due to water accumulation

Initiatives to investigate the influence of insulation system design on CUI

There have been few studies that have investigated the influence of insulation system design on CUI discussed in this section. One current such project has commenced in The Netherlands, where a 3 year European funded project [Interreg Vlaanderen-Nederland, 2020] includes the testing of different insulation system designs for improved CUI performance.

CUI direct screening non-intrusive inspection - PEC and radiographic techniques

The Lockheed Martin report [2016] evaluated the status of the latest CUI detection techniques and innovation landscape (Figure 7).

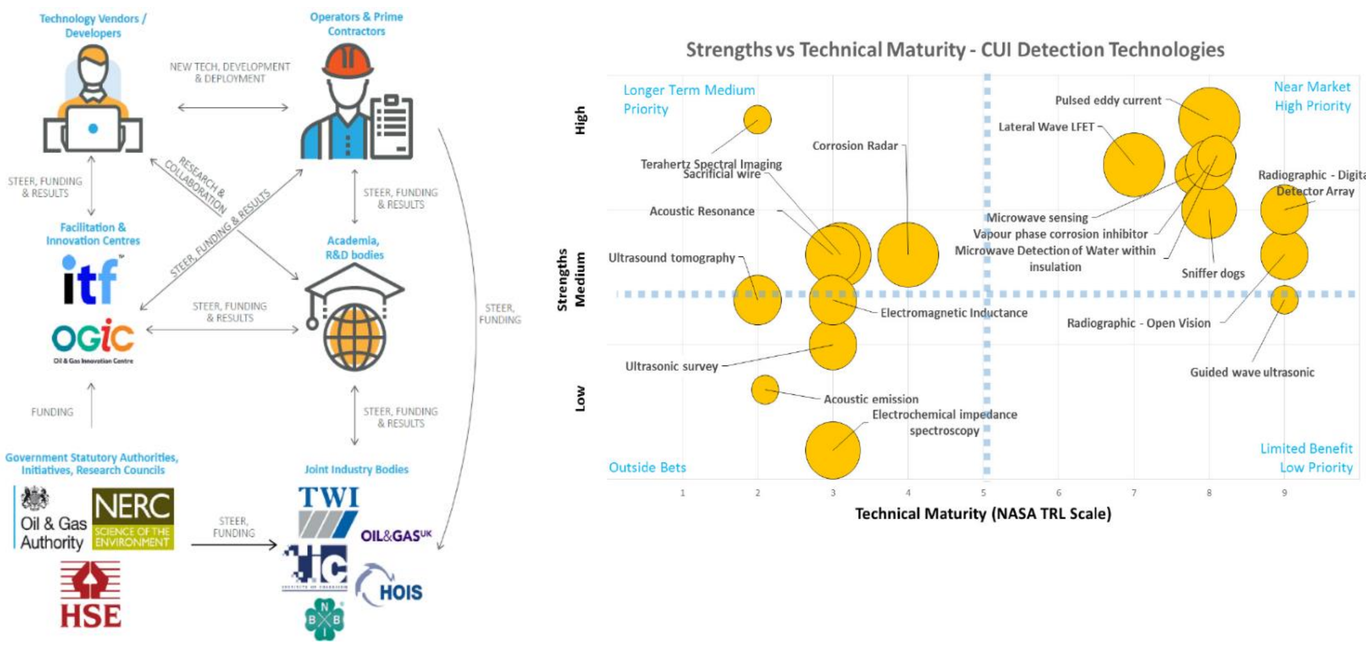

Figure 7. CUI detection innovation landscape and technology evaluation status from 2016 Lockheed Martin landscaping study.

This study identified **PEC (Pulsed Eddy Current)** and **RTR (Real Time Radiography)** as the most promising of the market ready techniques although it did not address their respective application limits in sufficient detail. PEC screens for metal loss (although accurate quantification of remaining wall thickness is less reliable) whilst RTR (new handheld rigs for faster deployment) screens for evidence of corrosion product and may detect water. Neither technique has been widely deployed as an alternative for insulation removal and inspection so there are limited published data to allow meaningful comparison.

Both techniques share the problem of added planning complexity due to application limits and neither can be used as widely as insulation removal and inspection. Insulation system data (e.g. insulation type and thickness) are also needed to understand where they can be applied and how to address gaps, which also adds to inspection complexity. Manufacturers supply charts which help to determine where the techniques are effective, or in the case of PEC, defect size detection limits.

For **PEC**, the limits of detectable metal loss are heavily dependent on the volumetric shape of defects. Manufacturers base their quoted detection accuracy on machined cylinder defect testing which is converted to axial/depth data, but non detectable defect axial/depths could be much larger for real CUI defect volumetric shapes, for example the volume of a cone is a third of the volume of a cylinder. There is no published library for CUI defect volumetric shapes at present. For RTR hand-held rigs, one major manufacturer provides tables representing application limit effectiveness, but these do not cover all insulation system designs. The advantage of RTR over PEC is that it is immediately apparent if it is not working correctly.

For **RTR,** radiation exposure to the operating technician (as hand-held) must be considered. Compliance with Ionising Radiation Regulations ([UK Legislation, IRR, 2017] or other national regulations) does not guarantee that the equipment can be deployed safely for all purposes. In the US, Canada, and Australia the approach is less stringent than in Europe, where this technology has yet to be deployed. Rigs that incorporate advanced shielding incur a weight penalty, and operator testing in Europe to measure radiation exposure has commenced but is so far limited. The exposure is dependent on many factors including geometries and access. For RTR, access constraints are in general greater compared with PEC due to the mode of deployment.

Neither RTR or PEC are currently cheaper or significantly less resource intensive than insulation removal and inspection across all applications. They may be equivalent (PEC), or significantly faster (RTR) for long simple pipe geometries of certain insulation system designs. PEC may be cost effective for vessel hot spots. However, operating plants are generally congested, especially offshore and onshore in Europe, which may explain why the best performance and safest use of these techniques has been where there are many kilometers of insulated piping (US/Canada/Australia).

TAXI™ (Trip Avoidance X-ray Inspection) is a recent technique which is not CUI specific, but applicable. It was designed to limit the impact of conventional radiography on nucleonic equipment instrumentation. It is limited in use to smaller diameter piping and unlikely to be more cost effective than insulation removal and inspection. However, it is believed to be quicker than conventional radiography and may be a highly effective non-intrusive CUI tool to evaluate wall loss at suspect locations if a cost effective and reliable screening technique should be developed to locate these areas.

CUI indirect screening inspection or permanent monitoring

Thermography is a technique that has existed for a long time and it can be periodically hand deployed to detect the presence of water within insulation systems, to reduce traditional inspection coverage. It has not been used extensively in this way but perhaps should be. It may add deployment complexity, although measurements during night-time can accommodate the required temperature difference between ambient and pipe surface temperature and avoid emissivity problems with shiny metallic or ferromagnetic cladding or components of insulation systems. This technique could indicate false positives, for example where insulation is missing, and deployment timing is key if insulation dry-out can occur between wetting cycles (false negatives). Overall, thermography surveys could detect persistent water sources associated with the most severe CUI occurrences. This technique does not detect corrosion and is not yet a replacement for traditional inspection coverage.

Permanently deployed sensor technologies are being developed and marketed. Several types are commercially available. It is interesting that all the sensor technologies work differently and therefore may have different strengths and weaknesses. Their purpose is to target locations to indicate precursors of CUI in the hope that local humidity or water wetting can be detected, or by sensing coating deterioration, or acting as a sacrificial coupon that transmits metal loss data. The CUI-specific sensors are all designed to achieve wide surface coverage. If they succeed in reliably identifying local meaningful differences in conditions they offer the opportunity to drive timely preventative maintenance, for example to repair water ingress locations, and/or to reduce inspection costs by significant reduction in locations.

Sensors are either externally deployed (strapped to, or penetrating, the cladding), or internally deployed either at the metal surface or between the cladding and insulation. There is a significant advantage for brownfield assets for those that can be deployed without removing insulation or cladding.

At present, sensors have had limited deployment and it may take 15-20 years to gain sufficient confidence that these technologies locate CUI effectively before it becomes an issue. Cost effectiveness is entirely reliant on remaining asset life and proof of reliability to reduce conventional inspection costs.

Figure 8 provides an example of the current sensor technology innovation landscape for CUI. It has changed significantly since the Lockheed Martin study in 2016. Some sensor types that measure wall loss are finding use for internal corrosion monitoring where locations can be predicted (e.g. erosion) or where spot sensing is effective (e.g. internal corrosion at high system temperatures where online manual NDT is not possible). Sensors designed specifically for CUI are aimed at detecting the onset of CUI and may need to be combined with prediction methods to deliver equally reliable but more cost-effective schemes compared with conventional approaches.

There are still many questions, for example whether high ambient humidity will affect humidity sensor data, or whether sensors deployed at the metal surface will promote crevice corrosion. Another concern is whether sensors can be deployed effectively for small bore attachments and geometries.

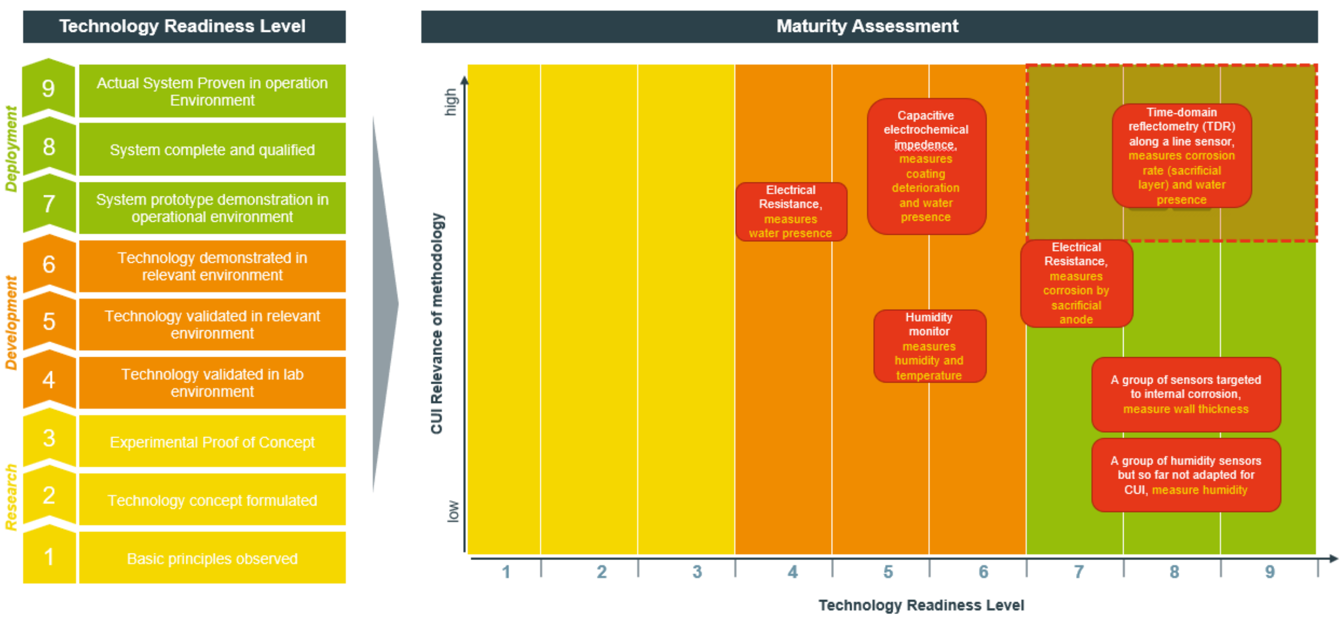

Figure 8. Innovation landscape of CUI sensor technologies.

Initiatives to trial or investigate CUI direct and indirect screening methods

There are many examples of ongoing studies which explore non-intrusive techniques and sensor technology reliability, and some examples are provided below.

The UK joint industry funded HOIS project has long evaluated non-intrusive inspection techniques, most recently in a joint project with OGTC spanning 2017-2019 with focus on CUI. The overall results and learnings have been published by [Burch, 2020]. Field trials were not conducted, but some field experiences were compiled. The work involved working with machined replicas of real CUI defects and trying to simulate the effect of corrosion product. A further project has been sanctioned in 2020 to continue to investigate PEC. An operator in Norway has also held a series of trials since 2018 on a variety of test piping with pre-existing CUI using several techniques including PEC, but the results have not been published.

For RTR, individual service providers and operators in Europe are starting to execute trials to examine radiation exposure but this is not publicly shared, and initial results appear to indicate the need for further safety controls. New product designs may reduce exposure but there is still further work to be carried out.

In 2020 SINTEF initiated a three-year “PredictCUI” project in collaboration with several Norwegian operators, research partners and the research council of Norway to predict migration of water liquid and vapour within insulated systems in order to develop the use of humidity sensors to mitigate CUI [Sintef, 2020]. It is evident from the project proposal that there is more to understand fundamentally in this area. It is unclear what type of insulation system designs it will cover, and whether it will address other types of sensor, but it will include both laboratory and field testing. Curtin University in Australia is launching a JIP which makes use of laboratory and field data, including sensors, to train a CUI predictive model [Curtin University, 2021]. Some petrochemical and oil & gas operators are designating parts of their plant to trial sensor technologies.

4. Confidence in new CUI innovations

The most common problem for CUI innovations for the management of CUI is uncertainty in reliability limits, and how to collect and share performance data, both positive and negative. Given that the majority of effort related to managing CUI is often already targeted on conventional inspection of the most critical equipment, innovations need to eliminate or significantly reduce this inspection to be cost competitive, by extending intervals and/or predicting occurrence location, whilst still matching conventional insulation removal and inspection with respect to reliability. This must include the deployment investment and data management costs associated with the innovation. In other words, confidence in reliability is needed to achieve cost effectiveness for many products.

Given that it may take up to 15 to 20+ years for significant CUI to develop, it is important that operators not only share their historical data but continue to play a key role in facilitating short- and long-term trials to evaluate innovations, whether they be new or existing for many years but little deployed. This commitment appears to be equally important as the cost of the development of the actual technologies themselves.

Operators who invest significantly in measures to manage CUI, including periodical 100% stripping of insulation for inspection, offer the best prospect for assessing the progress of trials of new solutions, which should be run concurrently with existing schemes to gain confidence. Operators who traditionally spend less on inspection may not provide the required evidence within a short enough timescale to be useful. Technologies or designs that require significant investment and take time to verify could be counterproductive to the overall confidence in the application of new innovations if failures still occur. An incentive to trial innovations alongside any inspection scheme is that they may increase the effectiveness of the scheme, thereby justifying the investment by prevention of associated significant failures.

NDE and water monitoring (sensor) technologies may offer the best opportunities to demonstrate reliable solutions in a shorter timescale because it could be easier to assess their performance through a combination of field and laboratory trials. This relates to technologies that measure what may be replicated successfully in the laboratory, or verified more quickly with on-site testing, without waiting for CUI to develop.

Process plant is often congested and complex. The innovation landscape has shifted significantly over the past four years and the latest innovation initiatives are shifting to hands off approaches to optimise the deployment of personnel working closely around plant equipment, i.e. prediction and embedded monitoring. This is especially driven by increasing focus on decarbonisation for offshore installations e.g. by reducing travel. Hand deployed Non Destructive Examination (NDE) CUI screening techniques are not cost effective for all equipment. It would be beneficial if a technique can be applied to all equipment, not just certain parts of it, and is safe to work with.

Combinations of innovations may complement each other, but also care should be taken to avoid multiple innovations that may not work well together. When the strengths and weaknesses of innovations are more clearly understood, digital twin scanning technology may assist with improved planning by desktop visualisation of the insulated plant equipment geometry and key design information but is not yet applied to all operating plants. It should also be recognized that different climates and plant operating profiles may suit some technology solutions much more than others. What works in temperate climates may not necessarily be successful in humid climates.

5. Key Learnings

The key learnings from this review are:

1. CUI knowledge and understanding has so far come from field data and experience, but there are relatively few published datasets. The lack of a platform for consistent sharing of CUI experience in a more quantitative way has impeded sharing of knowledge that could have prevented significant failures. There are clear benefits in favour of having an independent organization that gathers, analyses and shares CUI experience in a consistent way.

2. It can take 15-20 years for any CUI technology to be validated in the field and CUI innovations suffer from limitations that laboratory testing and isolated field tests, to date, have not been capable of identifying. Current innovation projects aim to develop more confidence in technology performance and application limits over shorter periods by linking laboratory tests to field data.

3. Operators can prevent most critical equipment CUI failures by adopting reliable inspection schemes. Exceptions appear to be associated with unique combinations of factors which could be identified and avoided if more data are available.

4. Operators have an important role to play in innovation by sharing historical CUI data and hosting longer term field trials.

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