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Edited by S. Winnik

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S. Winnik

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European Federation of Corrosion (EFC) publications: Series introduction

The European Federation of Corrosion (EFC), incorporated in Belgium, was founded in 1955 with the purpose of promoting European cooperation in the fields of research into corrosion and corrosion prevention.

Membership of the EFC is based upon participation by corrosion societies and committees in technical Working Parties. Member societies appoint delegates to Working Parties, whose membership is expanded by personal corresponding membership.

The activities of the Working Parties cover corrosion topics associated with inhibition, education, reinforcement in concrete, microbial effects, hot gases and combustion products, environment-sensitive fracture, marine environments, refineries, surface science, physico-chemical methods of measurement, the nuclear industry, the automotive industry, computer-based information systems, coatings, tribo-corrosion and the oil and gas industry. Working Parties and Task Forces on other topics are established as required.

The Working Parties function in various ways, e.g. by preparing reports, organising symposia, conducting intensive courses and producing instructional material, including films. The activities of Working Parties are coordinated, through a Science and Technology Advisory Committee, by the Scientific Secretary. The administration of the EFC is handled by three Secretariats: DECHEMA e.V. in Germany, the Société de Chimie Industrielle in France, and The Institute of Materials, Minerals and Mining in the UK. These three Secretariats meet at the Board of Administrators of the EFC. There is an annual General Assembly at which delegates from all member societies meet to determine and approve EFC policy. News of EFC activities, forthcoming conferences, courses, etc., is published in a range of accredited corrosion and certain journals throughout Europe. More detailed descriptions of activities are given in a Newsletter prepared by the Scientific Secretary.

The output of the EFC takes various forms. Papers on particular topics, e.g. reviews or results of experimental work, may be published in scientific and technical journals in one or more countries in Europe. Conference proceedings are often published by the organisation responsible for the conference.

In 1987 the, then, Institute of Metals was appointed as the official EFC publisher. Although the arrangement is non-exclusive and other routes for publication are still available, it is expected that the Working Parties of the EFC will use The Institute of Materials, Minerals and Mining for publication of reports, proceedings, etc., wherever possible.

The name of The Institute of Metals was changed to The Institute of Materials (10 m) on 1 January 1992 and to The Institute of Materials, Minerals and Mining with effect from 26 June 2002. The series is now published by Woodhead Publishing and Maney Publishing on behalf of The Institute of Materials, Minerals and Mining.

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55 **Corrosion-under-insulation (CUI) guidelines**
Prepared by S. Winnik on behalf of Working Party 13 on Corrosion in Oil and Gas Production and Working Party 15 on Corrosion in the Refinery Industry

Abbreviations

ACFM	alternating current field measurement
AISI	American Iron and Steel Institute
ASME	American Society of Mechanical Engineers
ASTM	American Society of Testing and Materials
AWS	American Welding Society
BPSD	barrels per stream day
BS	British Standard
Cl-ESCC	chloride external stress corrosion cracking
CUI	corrosion under insulation
DCF	discounted cash flow
EFC	European Federation of Corrosion
HOIS	Harwell Offshore Inspection Services
ICI	Imperial Chemical Industries
IOM	Institute of Materials (formerly Institute of Metals; now Institute of Materials, Minerals and Mining)
ISO	International Organization for Standardization
KPI	key performance indicator
LCC	life cycle cost
LPO	lost profit opportunity
MPY	milli-inches/year
MTBF	mean time between failures
MTI	Materials Technology Institute
NACE	National Association of Corrosion Engineers
NDE	non-destructive examination
NDT	non-destructive testing
PSV	pressure safety valve
RBI	risk-based inspection
RTR	real-time radiography
SCC	stress corrosion cracking
SHE	safety, health and environment
SSPC	Steel Structures Painting Council
TSA	thermally sprayed aluminium
WP	Working Party

Dedication

This book is dedicated to Terry Hallett who worked for Shell (UK) and died unexpectedly in 2005. He was one of the key early contributors to the development of this book. His enthusiasm inspired his friends and colleagues, from within Shell and from other companies, into ensuring that the work he initiated would be completed. Corrosion under insulation (CUI) is not one of the work areas that typically inspires us, but, despite an exceptionally heavy work load, Terry spared no effort to further the interests and activities of both the UK CUI Forum and the EFC and played a key role in both associations. Terry will be remembered by all who came into contact with him for his sincerity and his sense of humour. He will be sorely missed.

As the lead author, I know that the book would not have been completed without the many contributions from many others. We all know that writing a book by committee is never easy. Special thanks are extended to Hennie DeBruyn (Borealis), Andrew Kettle (ChevronTexaco), Rob Scanlan (ConocoPhillips), Staffan Olsen (Scanraff), Carmelo Aiello (Ente Nazionale Idrocarburi), Nicholas Dowling and Maarten Lorenz (Shell), François Ropital (Institut Français du Pétrole) and John Thirkettle (UK CUI Forum) for their efforts throughout the development of this book.

Dr Stefan Winnik
Editor
ExxonMobil Chemical

1
Introduction

Corrosion-under-insulation (CUI) refers to the external corrosion of piping and vessels fabricated from carbon–manganese, low-alloy and austenitic stainless steels that occurs underneath externally clad or jacketed insulation owing to the penetration of water. By its very nature, CUI tends to remain undetected until the insulation and cladding or jacketing are removed to allow inspection or when leaks to atmosphere occur. CUI is a major common problem on a worldwide basis that is shared by all the refining, petrochemical, power, industrial, onshore and offshore industries. It is not a new problem, but it can be a serious problem. CUI has been responsible for many major leaks that lead to health and safety incidents, result in lost production and are responsible for the large maintenance budgets which are required to mitigate the problem.

Corrosion of austenitic stainless steels usually manifests itself as chloride external stress corrosion cracking (Cl-ESCC). Although Cl-ESCC [1] was first reported in 1965, not many references are available on the CUI of carbon–manganese steels and low-alloy steels up to 1980 when a meeting was held in November 1980 [2]. A review of this very successful 2 day meeting was given by Richardson [3] during a symposium which was held in 1983 [4], and was sponsored by the Association for Testing and Materials (ASTM), the National Association of Corrosion Engineers (NACE) and the Materials Technology Institute (MTI). It would appear that, when reviewing the literature from that meeting today, the problems reported in 1980 mirror the experiences currently being reported today.

Although numerous instances of CUI are reported annually, this has not been reflected in the production of many industry standards for insulation or measures to mitigate CUI. The first ASTM standard on thermal insulation materials relevant to CUI was adopted in 1971 [5]. NACE Task Group T-6H-31 first issued a report on CUI [6] in 1989 and later Task Group T-5A-30 was formed, which became an open forum for CUI problems and solutions. This led to the publication of a NACE recommended practice RP0198-98 [7] which was revised in 2004 [8]. A number of conferences and initiatives covering CUI and insulation materials have taken place since 1983 but the problem remains unresolved. It would seem that the incidence of CUI examples is not diminishing and would appear to be increasing, given the number of instances being reported. An NACE conference in 2003 reviewed similar topics covered back in 1983 which were illustrated by Delahunt [9] who presented an excellent historical perspective of the occurrence of CUI. A conference held in the UK in 2004 [10] had a similar theme and again suggested that CUI had not been mitigated and that instances of CUI were actually increasing. These instances led to the formation of an informal group (UK CUI Forum) [11] by corrosion and materials engineers from a number of major oil and gas producers in the UK specifically to share CUI-related information. The Forum has since expanded and now includes representatives from other industries. Collaboration between the UK CUI Forum and the European Federation of Corrosion (EFC) led to the development of this document, which hopefully will be regularly updated to reflect any major advances in the mitigation of CUI.

Why does CUI occur? CUI of carbon–manganese steels and low-alloy steels usually occurs when a number of conditions are fulfilled.

- Water or moisture must be present on the substrate in order to allow oxygen corrosion to occur. Water ingress is due to breaks in the insulation, cladding or jacketing which may have resulted as a consequence of poor installation or damage during service or simply be a result of deterioration over time. The principal sources of water are as follows.
  - External sources which include rainwater, deluge systems and process liquid spillage.
  - Condensation.

This water may be retained depending on the absorption properties of the insulation material and the operating temperature. Depending upon process conditions, saturated insulation may never have the opportunity to dry out completely.

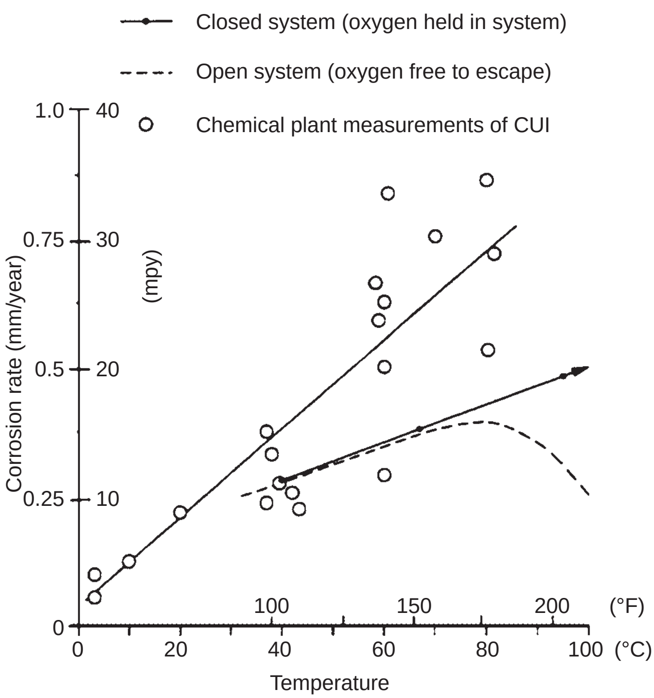
Contaminants that can cause problems on both carbon–manganese steels and low-alloy steels as well as on austenitic stainless steels need to be present. Chlorides and sulphides make up the bulk of the contamination and generally increase the corrosivity of the water. The source of the contaminants can be external such as environmentally borne chloride sources include sites situated in a marine environment (e.g. offshore), or wind-borne salts from cooling tower drift, or from periodic testing of firewater deluge systems. Contaminants can also be produced by leaching from the insulation material itself. In the presence of an applied or residual stress and temperatures exceeding 60 °C (140 °F), high chloride contents of water contribute to Cl-ESCC.

The operating temperature range of the piping or vessels should be between –4 °C (25 °F) and 175 °C (347 °F). This temperature range reflects the experience from the contributors to this document and is meant as guide to enable mitigation procedures to be developed. CUI problems have been reported outside this range; the majority of CUI occurrences are, however, within the specified range from –4 °C (25 °F) to 175 °C (347 °F). In general, the metal temperature will be approximately the same as the process operating temperature (for insulated equipment). However, if the insulation is damaged and/or highly humid conditions commonly exist, a process temperature significantly above 121 °C (250 °F) can result in metal temperatures low enough to cause CUI; therefore the CUI range is extended to 175 °C (347 °F). In addition, equipment subject to cyclic temperatures even outside this range (e.g. regeneration equipment) or dead legs (including 'cold' dead legs nominally operating below –4 °C and warming up to ambient temperatures) should be considered to be subject to CUI. Systems which utilise heat tracing require careful consideration.

The insulation type may only be a contributing factor since CUI has been reported under all types of insulation. However, the individual insulation characteristics can influence the rate at which CUI occurs. These include the following.

- Water-leachable contaminants such as chlorides and sulphates are present.
- There is water retention, permeability and wettability of the insulation.
- Any residual compounds may react with water to form hydrochloric or other acids.
- It provides an annular space or crevice for the retention of water and other corrosive media.
- It may absorb water.
- It may contribute contaminants that increase or accelerate the corrosion rate.
- Anodic reactions at the substrate surface may be caused by the presence of anode/cathode corrosion cell activity in a low-resistance electrolyte which may be at an elevated temperature or subject to cyclic temperature variations.
- CUI initiates owing to the presence of water, oxygen and other contaminants. Once water and oxygen are present on the steel surface, corrosion occurs through metal dissolution.

It follows that the insulation system that holds the least amount of water and dries most quickly should result in the least amount of corrosion damage to equipment. The absence or the presence of a damaged barrier



1.1 Corrosion rate as a function of temperature.

coating will permit direct contact between the water and the piping or vessel surface which will permit corrosion to occur.

The rate of CUI is determined by the availability of oxygen, the contaminants in water, the temperature, the heat transfer properties of the metal surface and the wet or dry condition of the surface. This in turn is influenced by the properties of the insulation materials. Damage can be general or localised. Service temperature is an important property as illustrated by Fig. 1.1 [12], which shows the effect of temperature of the corrosion rate of insulated carbon–manganese steels and introduces the concept of a closed system in which oxygenated water evaporation is limited, resulting in increased corrosion rates at higher temperature. This is the reason why CUI is such a problem as corrosion rates are often greater than anticipated.

In order to deal with and to mitigate CUI, strategies must be developed that involve many competencies in the plant such as corrosion, inspection, non-destructive evaluation, risk and safety evaluation, maintenance, unit operators and plant management. These strategies require the identification of zones and equipment at risk (Fig. 1.2). The risk analysis should consider the impact on the safety, the environment and the performance (reliability and availability) of the units.

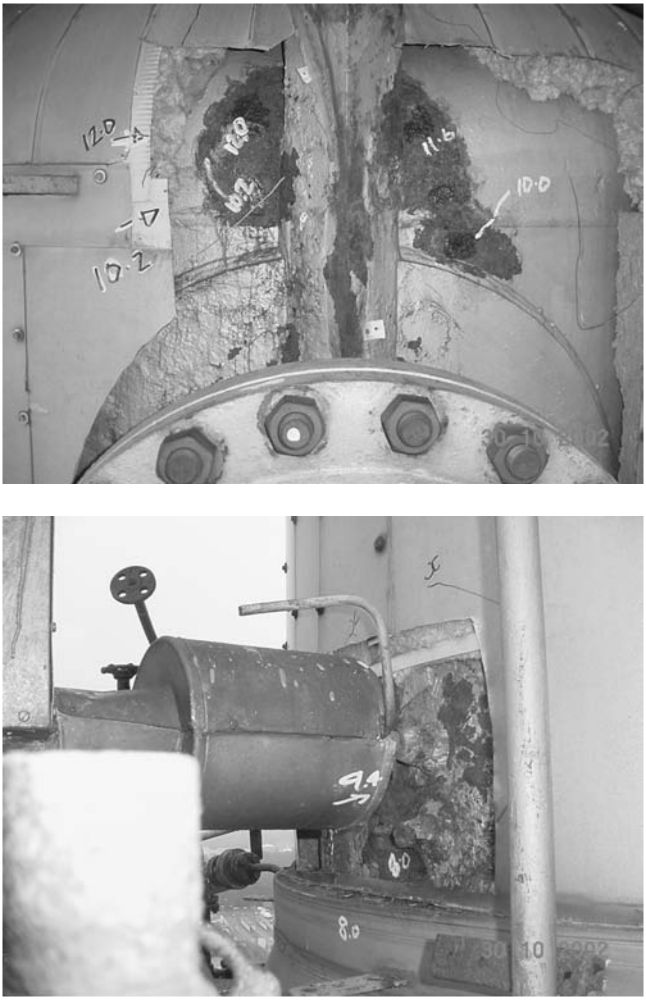
1.2 Examples of CUI damage to carbon steel piping and equipment.

1.1 Purpose of the document

The EFC working parties WP13 and WP15 have produced this guideline on CUI to promote such a strategy. The guideline reflects a consensus approach of this corrosion problem between the main European refining,

1.2 Cont'd

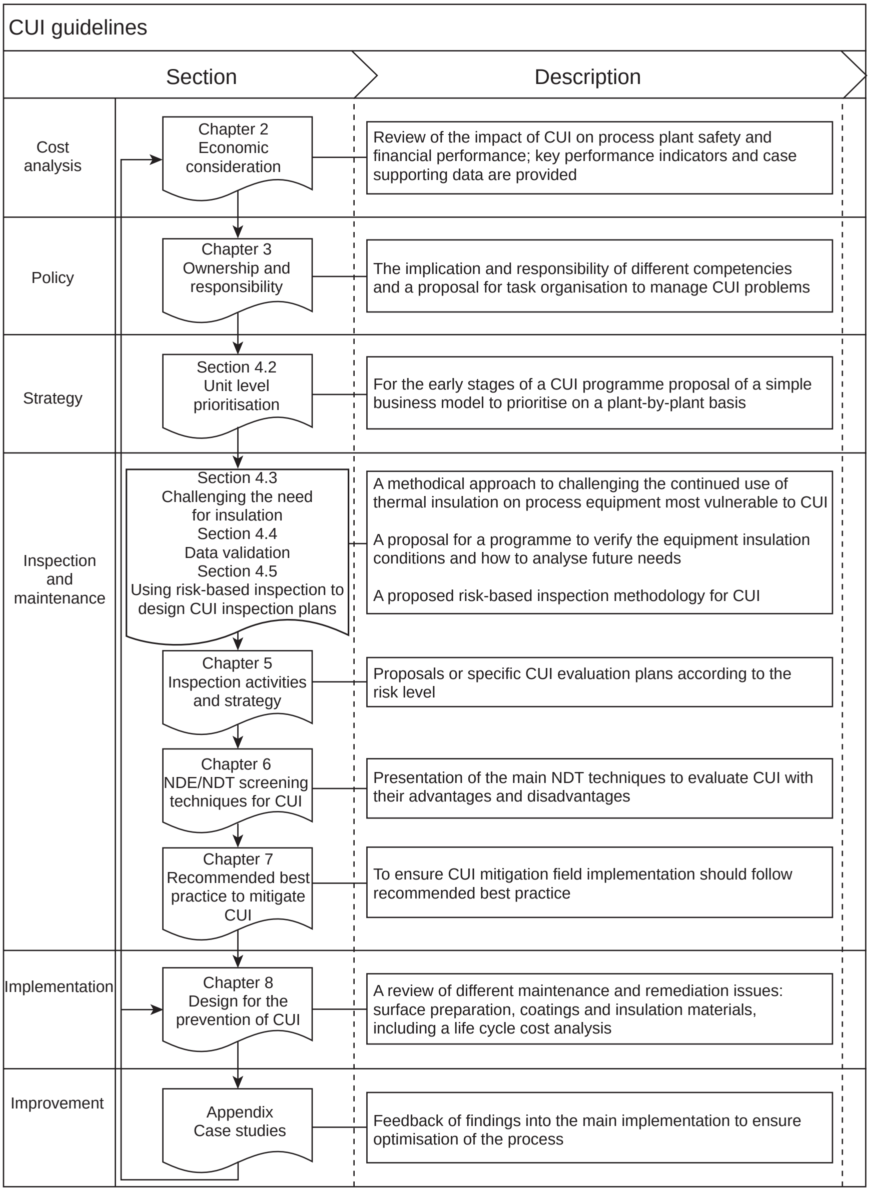
petrochemical and offshore companies who have contributed to producing this document. It is a collection of current experience primarily from the onshore and offshore oil and gas industries. These companies included BP, Chevron–Texaco, Conoco–Phillips, ENI, Exxon–Mobil, IFP, MOL, Scanraff, Statoil, Shell, Total and Borealis. The guidelines within this document are intended for use on all plants and installations that contain insulated vessels, piping and equipment. Any CUI evaluation will require detailed knowledge of the plant and the site where the equipment is located as significant geographical differences between plants will have to be taken into consideration. CUI cannot be visually detected during normal service



1.2 Cont'd

without removal of the insulation. Detailed knowledge and familiarity of systems, insulation characteristics and the overall objectives of management expectation of systems are essential together with continuity of an adopted strategy.

The intent of the document is to provide the basis of a unified approach to CUI management and will incorporate risk-based methodology whenever possible. The problems associated with CUI will be defined and will include the financial aspects of CUI. It must be stressed that, in order for this approach to succeed, it is important that both ownership and responsibility are clearly defined and demonstrated by management.



1.3 Schematic diagram showing the different sections of the guidelines and their relationship to the different concepts in the document.

The primary objective of this document is to provide the background to manage CUI effectively using a high-level risk-based approach to develop adequate inspection and maintenance strategies, using current best practice developed in the field. It is not intended that the document should provide a detailed prescription of when to inspect for CUI or to specify which of the many available non-destructive examination (NDE) and non-destructive testing (NDT) techniques to use or to specify a particular maintenance strategy. Guidance will be given on the most appropriate approaches to use, but the final decision will be left to the incumbent personnel who are responsible for the equipment that is susceptible to CUI.

The sections in the document will therefore include guidance on the following.

- Cost analysis.
- Policy.
- Strategy.
- Inspection and maintenance.
- Implementation.
- Improvement.

The different chapters and sections of this document and their relationship to the above concepts are shown in Fig. 1.3.

1.2 References

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9. J.F. Delahunt, 'Corrosion under insulation and fireproofing—an overview', in *NACE Corrosion Conference 2003*, Houston, Texas, NACE International, 2003, Paper 03022.
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12. F.N. Speller, *Corrosion—Causes and Prevention*, 2nd edition, New York, McGraw-Hill, 1935, p. 153 and Fig. 25.

2
Economic consideration

A fundamental step in the management process for any CUI or external corrosion control programme is a rigorous review of the current plant status. This review should include steps to identify the current incident rate and the potential incident rate, the impact of any failures on process plant safety, and the environmental and financial performances. A clear demonstration of the benefit to be gained versus the potential cost of maintaining the status quo is a key driver in ensuring senior management support for what can be a significant investment programme in any refinery or petrochemical, offshore or other process facility.

2.1 Statistical analysis

Analysis of inspection advice notes or recommendations, maintenance work orders and historical records should be carried out to determine a base case for failures and potential failure due to CUI or external corrosion. This information is best presented as an annualised figure, thus allowing year-on-year comparisons. Further partition of these data can prove useful in assessing the business risk ranking of process units used in high-level prioritisation (Chapter 4).

The number of CUI events that led to a loss of containment or leakage is the first key statistical figure. Each one of these events is likely to have significantly contributed to a lost profit opportunity (LPO) for a process facility as sometimes they result in unplanned downtime.

The number of CUI and external corrosion events that led to an additional engineering or maintenance work requirement is the second key statistical figure. Whilst each one is less likely to have a significant contribution to the LPO, as downtime can be better managed and planned, they are a clear indicator of the underlying trend of CUI on the facility.

2.2 Size of the issue

There are many ways of quantifying the cost associated with CUI and external corrosion. When collecting the data to make such an analysis, it is important to consider every detail, however small, as the cumulative effect will have a significant impact over the life of a facility.

Key factors to be considered are discussed below.

2.2.1 Safety and integrity

It is difficult to assign a cost to the safety impact of CUI or external corrosion in such an evaluation. However, it should always be the main priority and any event that has a personnel safety impact should be scored appropriately.

2.2.2 Environment

Environmental impact would include unscheduled flaring, noise, losses to drains and water courses, air or soil pollution and non-compliance with environmental regulations.

2.2.3 Revenue or production loss

The costs associated with any CUI or external corrosion event which impacts upon production rate or product quality should be calculated. Most facilities run a linear model for production and this should be used in conjunction with the midcycle margin to calculate a production revenue loss. The evaluation should account for the volume of product lost, requiring reprocessing or being downgraded. By using the midcycle margin, one can remove the influence of fluctuating margins on a year-by-year basis when fixing lost profit opportunities against operating and maintenance budgets.

2.2.4 Reputation

Reputation may be considered to be a soft and internal company issue. However, it is a major company issue as its impact may outweigh the sum total of all other costs. Also a potential loss of reputation may result in potential restrictions on a company's licence to operate.

The total LPO for a facility is the sum of all the above. Typical examples are quoted in the case history section.

2.2.5 Collateral damage cost

If a process line or piece of equipment failed by simple leakage and no other event occurred, then costing is simply the replacement cost of that item. If, however, another event occurred as a result of that leak, such as a fire, and other equipment was damaged, then this must be accounted for in the evaluation. In some circumstances, environmental or clean-up costs should be considered and these may be significant values.

2.2.6 Online leak sealing cost

In certain situations it may be acceptable to contain a leak or potential leakage area within an online leak-sealing device. Each device will have an associated manufacturing and installation cost. However, hidden behind this there may also be the cost of risk assessment to fit such a device and this should not be forgotten.

2.2.7 Repair and/or replacement, fabrication and installation costs

Repair and/or replacement of corroded equipment and piping are maintenance or project costs depending upon the value of the item to be repaired or replaced. Emergency or replacements (reactive repairs) are often performed as part of an unplanned outage. If items can be deferred to a period of planned maintenance or project activity by using restricted fitness for continued service criteria, then it is important to capture these costs also. These costs should be annualised from the time of the evaluation up to the next planned outage period.

2.2.8 Fitness for continued service

The cost of evaluating whether it is safe to leave an individual item of externally corroded equipment in service is not small. Based on the second key statistical figure referred to above, the value is likely to be large for a plant which has a high incidence of CUI or external corrosion.

2.2.9 On-stream inspection and non-destructive examination and testing

Care must be taken with this value as only costs associated with a loss of containment, associated collateral damage, or those inspections associated with a specific external corrosion or CUI event which warrants an inspection advice note or recommendation should be captured.

2.3 Key performance indicators

With any programme where statistical evaluation of events and financial performance is used as a method of enhancing justification, it will benefit the project cycle if key performance indicators (KPIs) can be identified and used.

In CUI programmes, the statistical KPIs could include, but are not limited to, the following items.

- Number of leaks due to CUI or external corrosion.
- Number of repairs for CUI or external corrosion.
- Number of CUI saves (capturing equipment and piping before the wall loss becomes significant).
- The risk reduction produced when an item is mitigated against CUI by inspecting and maintaining (remove insulation, inspect, blast, paint, reinsulate and seal).
- Reprioritisation of inspection due dates.

In CUI programmes, the financial KPIs could be items such as the following.

- LPO as a result of CUI or external corrosion.
- Maintenance repair cost due to CUI or external corrosion.
- Ranking of CUI or external corrosion in the facility revenue worst-actors listing.

3
Ownership and responsibility

Everyone who is working in a plant is responsible for ensuring that insulated systems are correctly installed, are inspected and are properly maintained. In addition to this, all personnel that are working in the plant are responsible for reporting damage to insulation systems when observed.

3.1 Senior management

Management should be aware of the problem of CUI and act so that both financial and human resources are available to manage the risk of CUI to an appropriate level. Management should also ensure that there is a culture within the organisation that reinforces the need to treat insulated systems in a way that avoids unnecessary damage that would promote CUI.

3.2 Engineering manager

It is the responsibility of an engineering manager to revise and improve specifications for vessel details, insulation, surface treatment, and supports and attachments to equipment in order to prolong the service life of equipment (see Appendix E).

3.3 Maintenance

It is the responsibility of maintenance departments to ensure that insulated systems are correctly installed and maintained (painting and insulation) using approved standards and that adequate quality checks are carried out. The responsibility of avoiding damage to insulation through plant engineering work lies with maintenance departments. The inspection and corrosion engineering function should ensure correct maintenance procedures and check their execution.

3.4 Operations

The operations department should ensure that damage to insulation or steam tracing leaks under insulation are reported immediately to the maintenance department for repair. The responsibility of avoiding damage to insulation through plant operational work lies with operations. This includes any changes required to equipment following process outside the operating window or when temporarily out of service (mothballing).

3.5 Inspection

Inspection departments should carry out inspection work to locate CUI on insulated systems, to assess the degree of corrosion damage and to determine whether continued safe operation is affected. This function should also ensure that equipment or piping is repaired or replaced where required. Ensuring that proper standards of painting and insulation are applied should be achieved through inspection. Inspection should also be involved during construction of new projects and plant changes.

3.6 Members of a project team; corrosion-under-insulation programme

Where a recognised ongoing CUI prevention programme is not in place and lack of maintenance has led to poor condition of the insulation of equipment, a number of major organisations have resorted to the setting up of dedicated CUI project teams to address the issues of CUI. This team may need considerable short-term funding to reinstate the refinery and/or process plant to an acceptable condition.

4

The risk-based inspection methodology for corrosion-under-insulation

4.1 Introduction

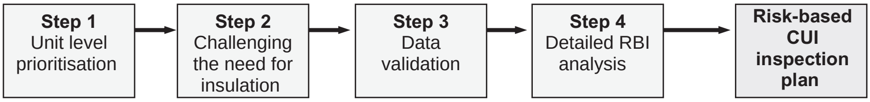
The risk-based inspection (RBI) methodology for setting up inspection plans (Fig. 4.1), which focus most effort on those items that possess the highest risk of failure, is generally accepted in the refining, petrochemical and offshore industries. For this reason a similar approach is recommended for CUI.

When introducing the RBI approach, risks will not be known. Insulated systems will have to be assessed in order to determine the appropriate risk levels and the associated inspection plans. In most practical situations it will be impossible to conduct such an effort on all insulated systems at once, because of limited resources and budget. For that reason, a unit level prioritisation step is introduced that may help to prioritise the RBI efforts for the different insulated systems. Using this approach, one will generally be able initially to direct RBI efforts to those insulated systems that feature the highest risks for operations. Section 4.2 will address this unit level prioritisation approach.

Once the units have been prioritised with respect to risk of CUI failure, it is recommended to challenge carefully the need for insulation. It is fairly obvious that the best way to eliminate CUI is to eliminate insulation. (Section 4.3 discusses the requirement for insulation.)

The RBI methodology makes use of actual operational and structural conditions of insulated systems, and not the design conditions. In order to obtain valid information from the RBI analysis it is important to be sure that all input data are correct. To this effect, data validation is described in Section 4.4, and the aim of this validation is to prevent errors in determining the risk of CUI failure.

Section 4.5 presents the RBI analysis for CUI, which consists of a condition assessment of insulated systems, a risk level determination according to the probability of CUI failure and the consequence of CUI failure, and the resulting CUI inspection plan based on that risk level. Once established,



4.1 The four steps for applying a risk-based CUI inspection plan.

this inspection plan is used periodically to assess the condition of the insulated systems, where the frequency and extent of the inspection efforts will depend on the risk level determined. Future inspection results shall also be used to reassess the initial risk level, which might lead to an adjustment of the risk level and, consequently, to a less or more intensive inspection scheme. The CUI inspection plan will also initiate maintenance tasks depending on the condition encountered.

4.2 Unit level prioritisation

As with any cross-facility programme it is often difficult to identify where to start to gain the maximum benefit within an acceptable time frame. The programme can take several years to complete one cycle and the available resource and budgets are often limited, even with senior management support. Identifying the areas of the process plant which are at risk from CUI and which have a large impact on business is fundamental to the success of the initiative.

The RBI methodology, as discussed in detail in Section 4.5, is often used to evaluate in detail the probability and consequence of a potential failure and thus to provide a guide to inspection priorities and schemes. However, in the early stages of a CUI control programme a simpler business model can offer a way to prioritise on a plant-by-plant basis.

The simple business model described below is one example of deriving a priority plan for a given programme based upon the 'risk to business'. It is based upon a subjective assessment of plant condition and knowledge of process unit interactions. Users may wish to tailor the model to suit their own needs by applying different weighting factors for their own particular facility. An example of the spreadsheet used to make an assessment is shown in Table 4.1.

The consequence of CUI failure categories used are described as follows.

- *Total site shutdown A*. Does a failure due to CUI on the specific plant being assessed cause a total facility shutdown? For example, loss of process unit 1 would affect all downstream units if alternative feedstock were not available. Loss of the steam-raising plant would shut down a

Table 4.1 Specific example of a unit level prioritisation risk assessment to evaluate priority against business risk

Unit name	Total site shutdown *A*	Partial site shutdown *B*	Single unit shutdown *C*	Highly toxic release *D*	Highly flammable or explosive release *E*	High reputational impact *F*	Consequence to business total *H*	Plant condition *G*	Weighted score: unit level business risk
Score	(7)	(2)	(1)	(3)	(5)	(4)	Sum of *A* to *F*	Poor (7) Average (6) Good (5)	$G \times H$
Process unit 1	7				5	4	16	7	112
Process unit 4	7				5	4	16	7	112
Process unit 08		2		3	5	4	14	7	98
Process unit 7	7				5	4	16	6	96
Instrument air–fuel gas	7				5		12	7	84
Process unit 31	7					4	11	7	77
Process unit 36	7					4	11	7	77
Process unit 04		2		3	5	4	14	5	70
Process unit 02		2		3	5	4	14	5	70
Process unit 19		2		3	5	4	14	5	70
Process unit 01		2			5	4	11	6	66
Process unit 6			1	3	5	4	13	5	65
Process unit 3			1	3	5		9	7	63
Process unit 16		2		3		4	9	7	63
Process unit 17		2		3		4	9	7	63
Process unit 12			1	3	5		9	6	54
Process unit 05			1	3	5		9	5	45
Process unit 06			1		5		6	6	36
Process unit 10			1		5		6	5	30
Process unit 14			1		5		6	5	30
Utility water			1				1	7	7
Process unit 5			1				1	5	5

site that was heavily dependent on steam for heating and primary turbine drivers.

- *Partial site shutdown B*. Does a failure due to CUI on the specific plant being assessed cause a partial facility shutdown? For example, loss of the units that provide steam and fuel gas would affect the facility balance.
- *Single unit shutdown C*. Does a failure due to CUI on the specific plant being assessed have little or no effect outside that unit's boundaries? For example, the unit does not affect the operation of other units but may impact final product quality or available volume.
- *High toxic release D*. Does a failure due to CUI put plant personnel or the general public at risk from a toxic release? This should take account of process units that may have a significant environmental impact if a release were to occur.
- *Highly flammable or explosive release E*. Does a failure due to CUI put the plant or plant personnel at risk from a flammable or explosive release? Process fluids are such that a release would cause a significant fire or explosion.
- *High reputational impact F*. Does a failure due to CUI have an effect on the plant and/or company's reputation? Some incidents will not involve high costs but could be regarded intolerable by the public and/or the authorities.

The probability of a CUI failure is assessed as follows.

- *Plant condition G*. What is the known or perceived general condition and preventative maintenance of a given process unit? This information is available from historical records or subjectively from interviews with plant personnel. The score is higher for poor condition and lower for good condition.

In the simple model described, the risk-to-business total is derived from the sum of the business consequence factors *A* to *F*. The final weighted-risk ranking is the consequence to business (sum of *A* to *F*) multiplied by the probability of CUI failure, expressed by the plant condition *G*.

Once the weighted scores have been sorted from high down to low, a review of potential synergies between adjoining plants should be conducted to adjust the proposed schedule. Similarly, the scheduled shutdown or inspection and testing plans should be reviewed to assess whether there are any potential clashes or missed opportunities for progressing the CUI control programme.

4.3 Challenging the need for insulation

Dramatic increases in energy costs during the 1970s resulted in a tremendous drive in the refining and petrochemical industries to conserve process energy, thus resulting in the increased and in many cases excessive use of thermal insulation. There is a need to challenge the very use of thermal insulation in the fight against CUI.

The purpose of this section of the guidelines is to provide the user with a methodical approach to challenging the continued use of thermal insulation on the process equipment most vulnerable to CUI.

The methodology described below is also graphically presented as a decision flow diagram in Fig. 4.2 and Fig. 4.3.

4.3.1 Step 1: determining the material type and operating temperature range

Carbon steel or low-alloy steel equipment that operates continuously above 175 °C or below –4 °C does not normally suffer serious problems due to CUI. For austenitic stainless steel the temperature limits above 175 °C or below 50 °C are used for guidance in these guidelines. Steady or cyclical operation between the temperatures given above present a significant risk for CUI.

It is recommended that equipment that operates in the above temperature range and that is insulated for heat conservation and process control should be selected for further assessment.

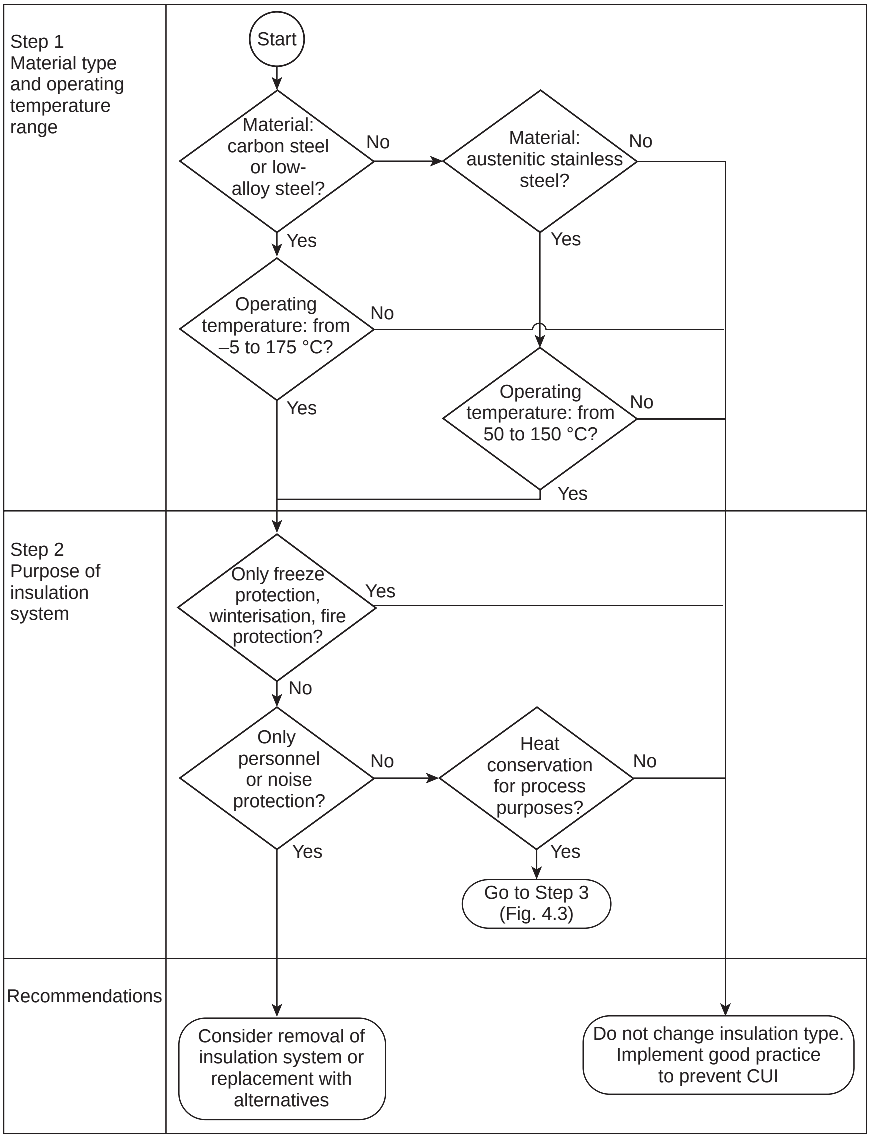
4.3.2 Step 2: determining the purpose of the insulation system

Plant equipment and piping are insulated for any or a combination of the following reasons.

- Heat conservation.
- Process control.
- Freeze protection and/or winterisation.
- Personnel protection.
- Noise control (acoustic purposes).
- Fire protection.

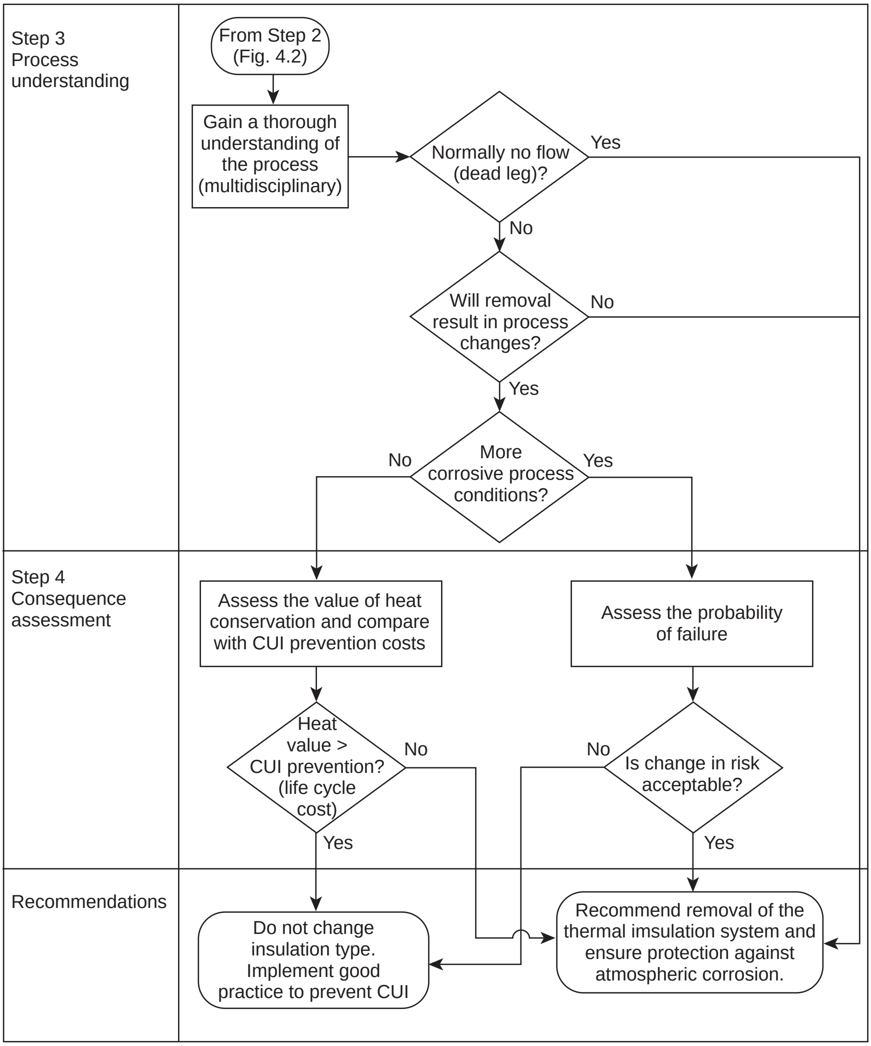
This information is often contained in the equipment and piping specifications for a particular facility, and it may be useful to gain an understanding of the various insulation codes used in the relevant specifications.

It is recommended that the use of thermal insulation for freeze protection or winterisation as well as fire protection should not be challenged as these form a part of the safety design of a plant that should not be compromised. For such systems, all the recommendations for protection against CUI contained in these guidelines should be implemented.



4.2 Challenging the need for insulation, methodology flow diagram: Steps 1 and 2.

All thermal insulation used for personnel protection and noise control should be considered for removal and replacement with alternatives. In the case of personnel protection, screens or protection bars may be used (see Appendix H). It may also be possible to use insulating coatings (ceramic coatings that reduce the surface temperature).



4.3 Challenging the need for insulation, methodology flow diagram: Steps 3 and 4.

4.3.3 Step 3: understanding the process environment

Before the removal or alteration of thermal insulation is considered on a system that is insulated for heat conservation or process control purposes, a thorough understanding of the process involved should be gained. Critical questions, such as the following, should be asked to further this understanding.

- Will removal of the thermal insulation system result in any process changes (phase changes)?
- What are the consequences of the process changes associated with the total removal of the thermal insulation system?
- Will removal of the thermal insulation result in a higher consequence category in an RBI assessment, i.e. increased risk?
- Will removal of the thermal insulation system result in more corrosive process conditions (e.g. may lead to condensation)? Does this change the probability of failure above that previously determined in an RBI assessment?

4.3.4 Step 4: assessing the consequences and probability of removing the thermal insulation system

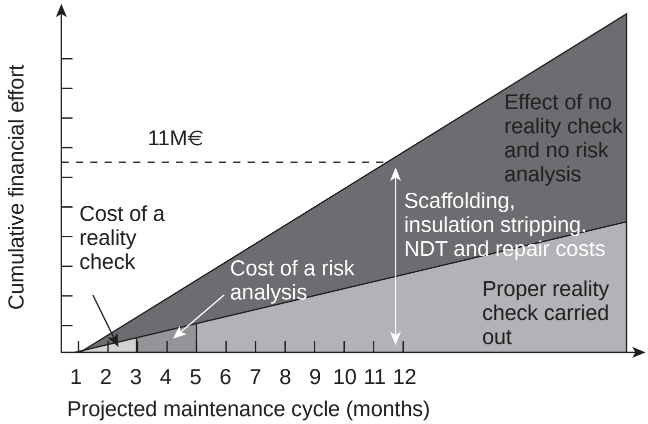
It is important to distinguish between economic consequences (e.g. increased energy costs and non-optimal process) and health and safety consequences. If health and safety consequences are the main drivers, then the use of the thermal insulation system should preferably be retained. If only economic consequences are involved, it is recommended that a thorough assessment of these costs be conducted and compared with the cost of preventing CUI (e.g. installing and maintaining a coating system under the thermal insulation).

Changes in the probability of failure due to internal corrosion should also be assessed. It is recommended that this be conducted using RBI principles. If no increase in the probability of failure is shown, it is recommended that the thermal insulation system be removed. Where permanent removal of insulation is carried out, the process should be captured by a management of change or plant change procedure so that the risks are evaluated and the relevant engineering records (e.g. drawings and engineering databases) are updated.

4.4 Data validation

4.4.1 The need for data validation

In Western Europe the costs of a CUI control programme can be very significant; however, those of inaction are even higher. The relative costs of action and inaction are the subject of Chapter 2 of these guidelines. The schematic diagram in Fig. 4.4 shows a rapid increase in costs associated with the logical actions taken to manage the risks associated with CUI. It also shows that, if a proper data validation has been carried out, the total costs of a CUI control programme may be significantly lower than if all insulated systems as present on the original design drawings are being analysed.



4.4 Schematic diagram showing the relative costs of data validation, the risk analysis and the actual maintenance, inspection and repair conducted. This provides an example of CUI annual losses for a 200 000 barrels per stream day (BPSD) 30-year-old coastal refinery with prevailing wind from the sea: about 11 M€/annum (lost profits, maintenance and inspection).

Hence, the objectives of data validation prior to entering an RBI assessment are to reduce the work and unnecessary expenditure associated with the RBI assessment of specific parts of the equipment.

4.4.2 Different aspects of a data validation

Examples of aspects to challenge in data validation are as follows:

- Check the necessity for thermal insulation of lines and vessels (as described in Section 4.3).
- Check that the system information provided is *correct* (pipe metallurgy, wall thickness, actual presence of thermal insulation, actual presence of coating and/or paint, and actual wetting frequency).
- Check that the operational conditions are *correct* (surface temperature, possible cyclic conditions, and actually in continuous or intermittent use).
- Check the actual system condition (based on inspection history: remaining wall thickness, coating and/or paint condition, and condition of the insulation system).
- If the insulated system is to be retired, then it should last for that required period which has to be taken into account when performing the risk analysis and determining the inspection and maintenance actions.

- If the vessel and/or piping is mothballed or otherwise out of service, then it may be unreasonable to devote time and money to assessing or refurbishing it.

4.4.3 Implementation of data validation

The simple process described below is one example of carrying out data validation. Users may wish to tailor the process to suit their own needs by including or excluding certain aspects such as mentioned in Section 4.4.2.

It is important that the engineer involved in the data validation makes a prescreen list of insulated pipe sections and pressure vessels within the unit of concern. Each unit shall have battery limits established on paper and flagged in the unit with plaques so that maintenance workers and subcontractors have clear indications of the limits of the unit.

Each insulated item appearing on the prescreen list shall be visually checked for the following, as an example.

- Insulation system presence.
- Insulation system condition.
- Item metallurgy.
- Item surface temperature.
- Item exposure to cyclic service.
- Item service condition.

A sample data validation list with examples is presented in Table 4.2.

4.4.4 Corrosion under insulation and mothballing of equipment

Equipment is taken out of service with the intention of either permanent retirement (scrapping) or reuse after a period or time (possibly with refurbishment) due to operational need in cyclic service. In both cases the equipment and piping must be rendered safe and hydrocarbon free. While permanent retirement can be considered a net loss, in the other case the equipment is important for the future of the plant and investment in a good mothballing procedure is critical. Specific mothballing procedures are required which preserve the equipment for future use and prevent any associated deterioration. In cyclic service a specific requirement for prevention against CUI is critical. Much equipment is not inspected for CUI because of the temperature range. Industry-wide the range for CUI is estimated as between –4 °C and 175 °C (carbon steels and low-alloy steels). However, out-of-service equipment will also deteriorate under ambient conditions owing to constantly saturated wet insulation which is not dried

Table 4.2 Example of a data validation list

Identifier	Is insulation present?	Insulation condition	Item metallurgy	Item surface temperature (°C)	Exposure to cyclic service?	Service condition?	CUI probable?
C-1001	Yes	Good	Carbon steel	112	Yes	In service	Yes
12″-1210-P1	Yes	Reasonable	Stainless steel	39	No	In service	No
TK-231	No	—	Carbon steel	102	No	In service	No
TK-401	Yes	Reasonable	Carbon steel	40	No	In service	Yes
E-1400	Yes	Reasonable	Aluminium alloy	83	No	In service	No
C-1203	Yes	Poor	Carbon steel	18	No	Out of service	Yes
E-1603	No	—	Stainless steel	243	No	In service	No

during the process cycles. As a consequence, even good-quality low-salt insulation will produce an accelerated corrosion rate when continually in contact with carbon steels and low-alloy steels. This effect should be recognised during the data validation process, where equipment and vessels which are out of service have to be assessed for CUI risks. The fact that a unit is out of service for only a few months will not have a great effect on the long term (40+ years) viability of the average carbon steel or low-alloy steel unit. However, after the unit has lain idle for 12 months, the risk for the unit shall be assessed and scored accordingly.

4.5 Using risk-based inspection to design corrosion-under-insulation inspection plans

The RBI methodology uses consequence of failure and probability of failure to determine the risk of failure. In the conventional RBI approach, the probability of failure is generally derived from corrosion rates, which can be used to estimate the remnant life of an item. However, the probability of a failure mode such as CUI is difficult to determine, because the corrosion rate is usually unknown. Since there are quite a number of factors that play a role in the process of CUI, the probability of CUI failure will be formed by a total score on a number of susceptibility factors, of which the operating temperature and the external environment (wetting extent and frequency) are the most important. Many companies will have general probability and consequence factors well established in their systems. The aim of this section is not to replace these, but to give an example of the methodology of RBI for CUI.

The following sections describe a possible process that can be used for an RBI assessment for CUI.

4.5.1 Preparation of a risk-based inspection analysis

An RBI analysis starts with compiling the detailed asset integrity data for the unit under study, which consist of the following.

- Process data, including actual operating windows.
- Engineering and design data and information on actual structural condition (see Section 4.4).
- Description and evaluation of degradation mechanisms.
- A compilation of inspection history and degradation analysis.

For the purpose of efficiency, the unit under study is divided into smaller corrosion loops or circuits, which are sections of the unit that are operating under similar conditions, are exposed to specific corrosion phenomena and consist of similar materials.

4.5.2 Consequence of corrosion-under-insulation failure

The next step in the RBI process for CUI is to determine the consequence of failure. A total of five consequence classes for economics, for health and safety and for environment are considered in this example, but every company can use its own set of consequence classes. For the consequence assessment the consequence score table (Table 4.3) can be applied.

4.5.3 Probability of corrosion-under-insulation failure

When the consequence of failure has been established, the probability of failure is determined. This assessment distinguishes between carbon steel or low-alloy steel, and austenitic stainless steel. For austenitic stainless steel the term CUI refers to Cl-ESCC. Chlorides in the permeated water can, depending on the temperatures and concentration, cause external stress corrosion cracking (SCC) in AISI type 300 series austenitic stainless steel. Cl-ESCC typically is found in stressed areas (such as welds), where chloride ions dissolved in water are in contact with type 300 series stainless steel at temperatures above 50 °C (a temperature of 50 °C is used for guidance in these guidelines).

As explained at the start of this section, the susceptibility to CUI or Cl-ESCC failure is taken as the indicator for the probability level.

4.5.4 Susceptibility factors

Score tables are used to determine the level of CUI or Cl-ESCC susceptibility. In the susceptibility tables, weighted scores can be awarded to a number of factors, which should include at least the key factors operating temperature and external environment (wetting extent and frequency). In these guidelines these key factors have been supplemented by five other factors contributing to the susceptibility to CUI (a total of four for Cl-ESCC). The user may decide to change or add to the susceptibility factors in order to fit specific conditions. The seven susceptibility factors used in this example are explained below.

- *Operating temperature* is a very important aspect of the item's susceptibility to CUI. In cyclic service (or temporary temperature changes), the temperature range corresponding to the most critical temperature reached should be taken. The occurrence of Cl-ESCC below 60 °C is very rare and, as a conservative approach, 50 °C is used for guidance in these guidelines. Above 175 °C, Cl-ESCC is seldom found; however, the item may still have a high susceptibility as it will be exposed to the most vulnerable temperature range of 50–175 °C during start-up or shutdown.

Table 4.3 An example of five consecutive consequence classes

Risk assessment matrix level	1	2	3	4	5
Health and safety	*No or slight injury* First aid case and medical treatment case; does not affect work performance or cause disability	*Minor injury* Loss time injury. Affects work performance, such as restriction to activities or a need to take a few days to recover fully (maximum 1 week)	*Major injury* Includes permanent partial disability. Affects work performance in the longer term, such as prolonged absence from work; irreversible health damage without loss of life, e.g. noise-induced hearing loss, or chronic back injuries	*Single fatality* Also includes the possibility of multiple fatalities in close succession due to the incident, e.g. explosion	*Multiple fatalities* From an accident or occupational illness, e.g. chemical asphyxiation or cancer (large exposed population)
Economics	*No or slight damage* No or very slight disruption to operation	*Minor damage* Brief disruption to operation	*Local damage* Partial shutdown that can be restarted	*Major damage* Partial or complete operation loss	*Extensive damage* Substantial or total loss of operation
Environment	*No or slight effect*	*Minor effect*	*Localised effect*	*Major effect*	*Massive effect*

The frequency of such temperature cycles should be taken into consideration.

- *Coating* is the main barrier between the steel surface and its environment. Therefore, the condition of the coating is crucial. As coatings degrade generally as a function of age, the older the coating, the greater is the probability of CUI. It should always be remembered that a poorly applied coating system can be worse than no coating at all, since it can accelerate corrosion by concentrating the corrosive effect on areas of coating breakdown. Equipment construction should be reviewed in detail to identify areas which, by design or poor fabrication, can act as a trap for water, resulting in coating breakdown. This will result in accelerated corrosion and an increased likelihood of both CUI and Cl-ESCC.
- *Cladding and insulation condition.* Although new cladding and insulation systems should be dry and virtually water tight, experience shows that, with age, water ingress is unavoidable. Mechanical damage, complex insulation geometries and/or inspection windows will increase the chances of water ingress. In Table 4.4 an example of an insulation deficiency and defect checklist is given, which will assist maintenance and inspection staff with assessing insulation damage that might lead to CUI.
- *Insulation type.* Fibre-type insulation materials, e.g. mineral wool and fibreglass, easily absorb water, whilst expanded perlite and foam glass, with a closed-cell structure, have no capacity to absorb water and therefore are less likely to contribute to CUI problems. Fibre-type insulation materials are commonly applied for hot insulation systems. The only way to reduce their contribution to CUI is by applying contact-free insulation techniques, whereby the insulation is held about 25 mm away from the steel surface.
- *Available corrosion allowance.* Thin-walled components will fail sooner owing to a certain CUI corrosion rate than will thick-walled components. However, the risk of CUI failure will not primarily be determined by the wall thickness, but by the available corrosion allowance. Although generally a conservative measure, the corrosion allowance indicates the tolerance of the component to wall loss before it will fail. By adding corrosion allowance, the susceptibility to CUI will not change, but the susceptibility to CUI failure will become lower. It is important to discriminate between the susceptibility to CUI, which is the chance that CUI will actually occur, and the susceptibility to CUI failure, which indicates the chance that CUI will lead to a failure; the latter is being considered here. For instance, in the case when a small bore connection in certain conditions will end up in a high-risk class, it may be considered that it should be replaced by a similar connection with a higher schedule

Table 4.4 An example of an insulation deficiency and/or defect checklist

	Tick if applicable
Caulking or sealant that has hardened and separated	
Circumferential cracks in glass-reinforced epoxy or glass-reinforced polymer jacketing	
Corrosion of cladding	
Damaged or loose cladding	
Damaged vapour barrier or stop	
Failure at bends (open joints)	
Foot traffic damage	
Gaps due to uncontrolled expansion or contraction	
Hot or cold spots	
Icing and/or condensation	
Incorrectly installed at flanges or valve boxes	
Longitudinal cracks in glass-reinforced epoxy or glass-reinforced polymer jacketing	
Missing insulation (not reinstalled after shutdowns)	
Missing insulation at flanges or valve boxes	
Missing self-tapers, rivets or stainless steel bands	
Rust stains and bulges in metal cladding	
Sagged insulation and cladding	
No termination at flanges or valves	
No termination in a vertical pipe or piece of equipment	
Water increase at penetrations (e.g. nozzles)	

(thicker wall and more corrosion allowance), which will reduce the point score of the CUI susceptibility table.

- *External coil and steam tracing*. The presence of steam tracing adds to the susceptibility to CUI since it may start leaking and, as such, provide a source of water for the corrosion process. The susceptibility score depends on the level of integrity of the steam-tracing system for which the following three factors are considered.
  - Coil corrosion in resistant material (copper, high alloys, e.g. Alloy 800, 825, etc.).
  - Coil installed using the highest level of quality control (e.g. 100% visual and leak test).
  - Heating medium is controlled and of good quality (non-corrosive and non-erosive).

  High-integrity design means that all the three aspects are satisfied. Mean-integrity design means that only two out of the three aspects are satisfied. Low-integrity design is used for all other systems.

- *External environment.* For CUI to occur, water needs to penetrate the insulation material and to contact the metal substrate surface. The degree of water ingress depends on the condition of the insulation material and the water sources and can be from rainfall, climatic environmental operating conditions, cooling water drifts, firewater, deluge systems, etc. Where no water can enter the system (inside buildings, no steam tracing, no sweating, etc.), the susceptibility to CUI will be insignificant and therefore the risk can be set to negligible by default.

4.5.4.1 Susceptibility score tables

Susceptibility score tables can be developed, both for carbon steel and low-alloy steel (less than 11% chromium) and for austenitic stainless steel, in order to establish the probability of failure class. An example of a susceptibility score table for carbon steel and low-alloy steel is shown in Table 4.5 and an example for austenitic stainless steel Cl-ESCC is shown in Table 4.6. Points should be awarded to each class, with more points for higher classes. The points awarded to any class can be determined by the user and can be dependent on their specific conditions. By adding the point score of the contributing factors, the total probability score can be determined.

Using the total score from the susceptibility score table, a probability class can be determined. For carbon steel and low-alloy steel, as well as for stainless steel, four probability classes are used in this example (but the user may decide to use more or fewer probability classes).

- Probability class negligible (total score 1-*A*).
- Probability class low (total score *A*-*B*).
- Probability class medium (total score *B*-*C*).
- Probability class high (total score greater than *C*).

The limits *A*, *B* and *C* have to be determined by the user based on experience and generally perceived corrosion rates in circumstances resembling the susceptibility conditions making up the total probability score.

It should be noted that the probability class, in combination with the consequence class, determines the risk level and hence there should be a sound relation with the inspection interval assigned to that corresponding CUI risk class. For instance, for a high-risk item with a predicted corrosion rate of 0.5 mm/year (although, generally, no corrosion rates are known for CUI, both literature and experience may provide rough indications of the worst-case values in certain conditions determined by the susceptibility factors) and a corrosion allowance of 2 mm, then the inspection interval should be significantly less than 4 years. However, for a low-risk item in the same conditions an interval of 4 years may be acceptable.

Table 4.5 Example of a susceptibility score table for CUI of Carbon Steels low-alloy steel, CS-1 to CS-4. Dead legs should be treated the same as the main pipe, except that the temperature should be estimated since the dead leg will be much cooler, especially if long. For example, a dead leg on a 230 °C line could easily be in the 50–175 °C metal temperature range for high probability. In the case of cyclic service (or temporary temperature changes), the range corresponding to the most critical temperature reached should be taken

Class	Operating temperature	Coating status when new or last applied	Cladding or insulation condition	Insulation type	Remnant corrosion allowance (example values only)	External coil or steam tracing	External environment	Score
CS-1	Constantly >175 °C or < −4 °C	Full quality assurance coating 8 years, or thermally sprayed aluminium coating 15 years	Good to engineering standards or renewed (<5 years)	Contact-free insulation, with regular inspection (every 5 years)	>4 mm	Not present	Inside building, not steam traced and not sweating Default negligible risk	?
CS-2	150–175 °C	Full quality assurance coating 8–15 years or conventional coating 8 years or thermally sprayed aluminium coating 15–20 years	Average condition, overall high-integrity design and construction	Expanded perlite, foam glass, closed-cell foam (good type)	2–4 mm	High-integrity design	Low wetting rate (<20% of the time)	?
CS-3	−4–49 °C and 111–175 °C	Conventional coating 8–15 years or thermally sprayed aluminium coating >20 years	Average condition, conventional design and construction	Fibreglass, asbestos, regular perlite, mineral–rock wool (<10 ppm Cl)	1–2 mm	Medium-integrity design	Medium wetting rate (20–50% of the time)	?
CS-4	50–110 °C or sweating conditions	Full quality assurance or conventional coating >15 years or unpainted or unknown	Poor condition, damaged, wet or broken seals	Calcium silicate, rock wool (no specification), unknown	<1 mm	Low-integrity design or leaking	High wetting rate (>50% of the time) (e.g. cooling-tower or deluge systems	?

Table 4.6 Example of a susceptibility score table for Cl-ESCC of austenitic stainless steel, SS-1 to SS-4. Dead legs should be treated the same as the main pipe, except that the temperature should be estimated since the dead leg will be much cooler, especially if long. For example, a dead leg on a 230 °C line could easily be in the 50–175 °C metal temperature range for high probability. In the case of cyclic service (or temporary temperature changes), the range corresponding to the most critical temperature reached should be taken

Class	Operating temperature	Shop coating or aluminium-wrap status and age	Cladding or insulation condition	Insulation type	External coil or steam tracing	External environment	Score
SS-1	Constantly >175 °C or <50 °C	Shop coating (full quality assurance) <8 years or aluminium-wrap <15 years	Good to engineering standards (undamaged)	Contact-free insulation, with regular inspection (every 5 years)	Not present	Inside building, not steam traced and not sweating	?
SS-2	>50 °C	Shop coating (full quality assurance) 8–15 years or maintenance coating <8 years or aluminium-wrap 15–20 years	Minor damage but with special precautions; sensitive areas	Expanded perlite, foam glass, closed-cell foam	High-integrity design	Low wetting rate (<20% of the time)	?
SS-3	>50 °C	Shop coating >12 years or maintenance coating >8 years or aluminium-wrap >20 years	Average condition; no special precautions; sensitive areas	Fibreglass, asbestos, regular perlite, mineral or rock wool (low chlorides <10 ppm)	Medium-integrity design	Medium wetting rate (20–50% of the time)	?
SS-4	50–175 °C or cycling conditions	Shop coating >15 years or maintenance coating >12 years or unknown	Poor condition; severely damaged wet or unknown	Mineral or rock wool (no chlorides specification), calcium silicate	Low-integrity design or leaking	High wetting rate (>50% of the time) (e.g. cooling-tower or deluge systems)	?

Table 4.7 Example of a generic risk matrix [1] (MTBF, mean time between failures)

Probability *F* of failure	Category	Consequence				
		A	*B*	*C*	*D*	*E*
$F > 0.050$ MTBF < 2	5 (very likely)	Medium	High	High	High	High
$F = 0.015$ MTBF = 7	4 (somewhat likely)	Low	Medium	High	High	High
$F = 0.01$ MTBF = 10	3 (unlikely)	Low	Medium	Medium	High	High
$F = 0.005$ MTBF = 20	2 (very unlikely)	Low	Low	Medium	Medium	High
$F < 0.0025$ MTBF = 38	1 (practically impossible)	Low	Low	Low	Medium	Medium
Safety (instant visibility)		No injury	Minor injury	Medical treatment	Serious injury	Fatalities
Health (long-term visibility)		No effect	Minor impact	Temporary problems	Limited impact on public	Serious impact on public
Environment		No damage	Minor impact; no response	Limited response	Significant response	Full-scale response
Economic loss (€)		$<5 \times 10^3$	5×10^3–10^5	10^5–10^6	10^6–10^7	$>10^7$
Public disruption		None	Minimal	Minor	Small community	Large community

Table 4.8 An example of a risk matrix to determine the CUI risk of failure from probability and consequence classes

		SUSCEPTIBILITY TO CUI FAILURE	CUI RISK CLASS				
PROBABILITY CLASS	H	TOTAL SCORE > C	L	MH	H	E	E
	M	TOTAL SCORE B-C	L	M	MH	H	E
	L	TOTAL SCORE A-B	N	L	M	MH	H
	N	TOTAL SCORE 1-A	N	N	L	M	MH
CONSEQUENCE CATEGORY		ECONOMICS (€)	NO/SLIGHT DAMAGE	MINOR DAMAGE	LOCAL DAMAGE	MAJOR DAMAGE	EXT. DAMAGE
		HEALTH & SAFETY	NO/SLIGHT INJURY	MINOR INJURY	MAJOR INJURY	SINGLE FATALITY	MULTIPLE FATALITIES
		ENVIRONMENT	NO/SLIGHT EFFECT	MINOR EFFEFT	LOCALISED EFFECT	MAJOR EFFECT	MASSIVE EFFECT
CONSEQUENCE CLASS			NEGLIGIBLE	LOW	MEDIUM	HIGH	EXTREME

N = Negligible
L = Low
M = Medium
MH = Medium-High
H = High
E = Extreme

4.5.5 Risk of corrosion-under-insulation failure

Using the determined probability and the consequence classes, the CUI risk class can be established using a typical risk matrix such as given in Table 4.7 [1] or a risk matrix designed for CUI for carbon steel and low-alloy steel as well as stainless steel as given in Table 4.8. The risk assessment matrix or table can have any form depending on each individual company's philosophy, but must be consistent with the risk assessment procedures for other hazards.

The final step is to link the determined risk class to the appropriate inspection and maintenance strategy. Distinction shall be made between strategies for carbon steel and low-alloy steel and for stainless steel.

4.6 Reference

1. European Commission for the 'GROWTH Programme, Research Project RIMAP Risk Based Inspection and Maintenance Procedures for European Industry', GROWTH Project G1RD-CT2001-03008 'RIMAP', *D4.2 Petrochemical Workbook*, Document 4-43-F-2004-01-1, 2004, p. 27.

5 Inspection activities and strategy

The intent of this chapter is to provide an overview of a sample inspection strategy that can be applied to all equipment (including piping) in addressing the problem of CUI. Individual companies may have their own strategies that they consider appropriate. The inspection plan strategy applied is dependent on and interacts with the principles and results of Section 4.3 and Section 4.5. Removal of insulation, external visual inspection and damage evaluation using NDE or NDT are the key issues proposed. Whilst non-intrusive techniques (NDE and NDT inspection can be performed without removal of insulation) may be used to assist the evaluation for corrosion, it is the general consensus of opinion in the refining and offshore industry that none of the NDE and NDT methods available alone can provide an adequate level of confidence in their sensitivity to detect and quantify CUI at the time of writing.

5.1 General considerations

There are several ways of detecting CUI on piping systems. Detecting CUI on vessels is generally more difficult, but it is possible using some techniques. Before selecting NDE and NDT for the detection of CUI consideration should be given to the following.

- Utilised metallurgy (carbon steel, stainless steel, etc.).
- Operating conditions.
- Insulation type and thickness.

Selecting an NDT technique for detecting CUI also requires detailed knowledge of the piping system or equipment layout as well as the advantages and disadvantages with a cost-to-benefit ratio for each technique.

Highly suspect areas that should be considered for CUI inspection include penetrations and damaged insulation. These are detailed below.

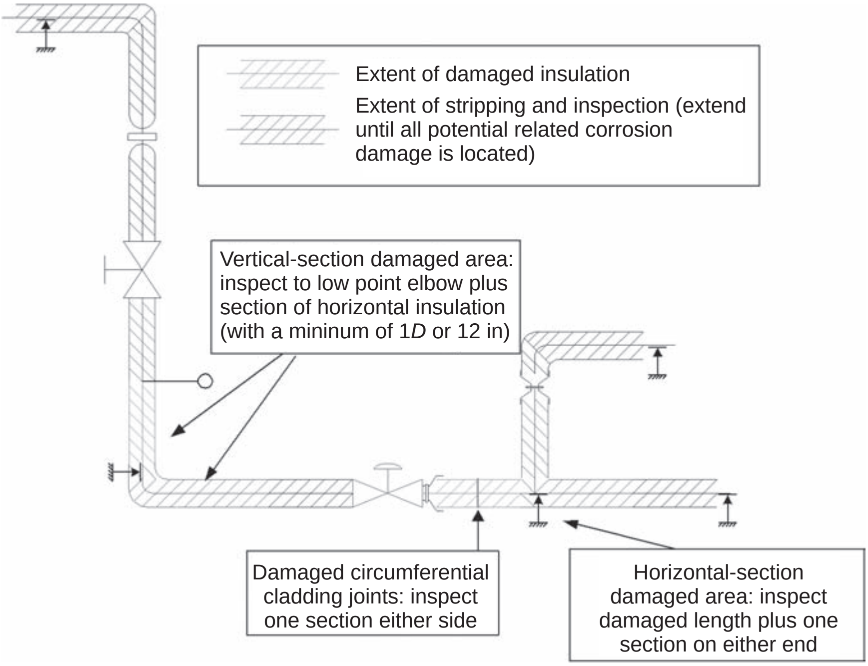
- *Penetrations*.
  - All penetrations or breaches in the insulation jacketing systems such as dead legs, hangers and other supports, valves and fittings,

bolted-on pipe shoes, ladders and platforms, and vessel nameplates attached by welding.
  - Steam-tracer tubing penetrations.
  - Termination of insulation at flanges and other components.
- *Damaged insulation areas*.
  - Damaged or missing insulation jacketing.
  - Termination of insulation in a vertical pipe or piece of equipment.
  - Caulking that has hardened or separated or is missing.
  - Bulges, staining of the jacketing system or missing bands.
  - Low points in systems that have a known breach in the insulation system, including low points in long unsupported piping runs.
  - Carbon steel or low-alloy steel flanges, bolting and other components under insulation in high-alloy piping.
- *Other areas*.
  - Areas exposed to sources of water such as mist overspray from cooling towers, to steam vents, to deluge systems or to process spills, ingress of moisture or acid vapours.
  - Carbon steel systems, including those insulated for personnel protection, operating between –5 ºC and 175 ºC.
  - Carbon steel systems that normally operate in service above 175 ºC but are in intermittent service or are subjected to frequent outages.
  - Dead legs and attachments that protrude from the insulation and operate at a different temperature from that of the active line.
  - Systems in which vibration has a tendency to inflict damage on insulation jacketing, providing paths for water ingress.
  - Steam-traced systems experiencing tracing leaks, especially at tubing fittings beneath the insulation.
  - Systems with deteriorated coating and/or wrappings.
  - Cold service equipment consistently operating below the atmospheric dew point.

5.2 Typical locations on piping circuits susceptible to corrosion-under-insulation

Piping systems may have specific locations that are more susceptible to CUI (Fig. 5.1). These include the following areas.

- All penetrations or breaches in the insulation jacketing systems including the following.
  - Dead legs (vents, drains, etc.).
  - Pipe hangers and other supports.
  - Valves and fittings (irregular insulation surfaces).
  - Bolted-on pipe shoes.
  - Steam and electric tracer tubing penetrations.



5.1 Example of piping areas of concern.

- Termination of insulation at flanges and other piping components.
- Damaged or missing insulation jacketing.
- Insulation jacketing seams located on the top of horizontal piping or improperly lapped or sealed insulation jacketing.
- Termination of insulation in a vertical pipe.
- Caulking which has hardened, separated or is missing.
- Low points in piping systems that have a known breach in the insulation system, including low points in long unsupported piping runs.

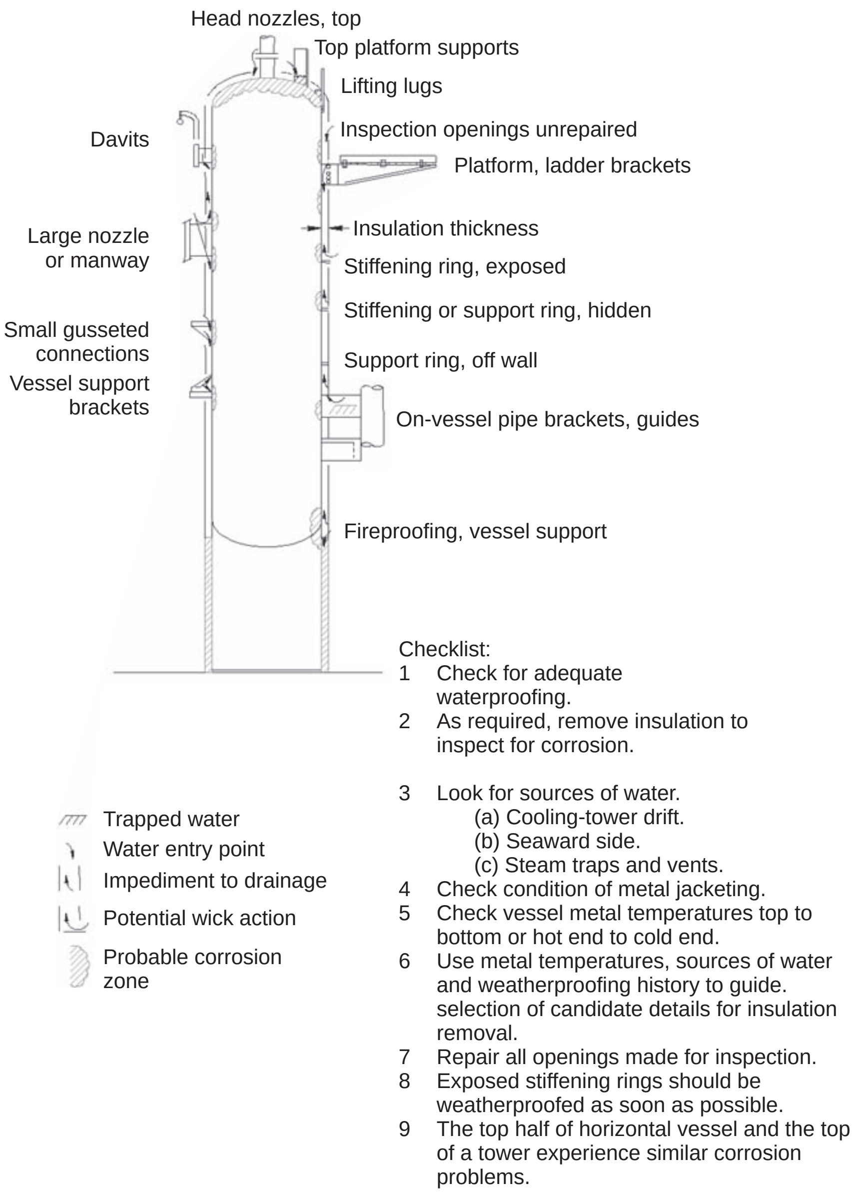
Particular attention should be given to locations where insulation plugs have been removed to permit piping thickness measurements on insulated piping. These plugs should be promptly replaced and sealed.

5.3 Typical locations on equipment susceptible to corrosion-under-insulation

5.3.1 Vessels, columns and tanks

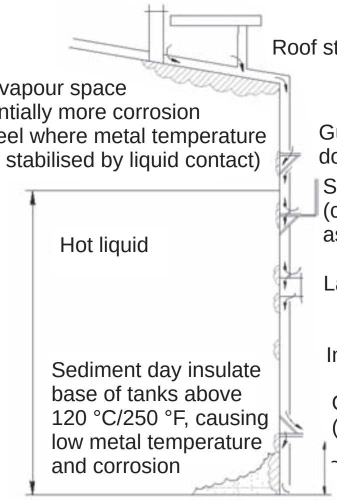
Specific areas of focus on pressure vessels (Fig. 5.2), columns, tanks (Fig. 5.3), and other insulated vertical equipment are detailed below.

- Termination of insulation at flanges.
- Rings for insulation, particularly in vertical head and bottom zones.



5.2 Example of vessel areas of concern.

- Stiffening rings for vacuum design (vessel or column).
- Insulated skirt zone attached to items and about 0.5 m under the weld of skirt (vessel or column).
- Insulated leg supports for small vessels.



General notes:

1 Water entering roof insulation can cause severe corrosion of walls as well as roof, where impediment to drainage exists. Seriously defective roof weatherproofing can quickly destroy a tank if metal temperatures permit.
2 Prolonged flooding of tank area basin due to environmental restrictions on draining is a cause of severe corrosion around base of tank.
3 Routinely inspect weatherproofing and steel. Repair insulation damage resulting from inspection.
4 Weatherproofing and design corrections are essentially the same as for vessels, except for roof–wall joint.

5.3 Example of tank areas of concern.

- Damaged or missing insulation jacketing.
- External base ring of insulated tanks.
- Pipe and flange on the pressure safety valve (PSV).
- Temporary insulation installations.

Particular attention should be given to locations where insulation plugs have been removed to permit piping thickness measurements on insulated piping. These plugs should be promptly replaced and sealed.

5.3.2 Heat exchangers

Specific areas of focus on heat exchangers and other insulated horizontal equipment are detailed below.

- Termination of insulation at flanges.
- Termination of saddles insulation.
- Rings for insulation.

- Damaged or missing insulation jacketing.
- Pipe and flange on PSV.

Attention should be given to locations where insulation plugs have been removed to permit piping thickness measurements on insulated piping. These plugs should be promptly replaced and sealed.

5.4 Examples of a risk-based inspection plan

The following examples provide an indication for the scope of inspection that is required when considering the likelihood of CUI. RBI should be used to minimise the economic impact prior to establishing ongoing CUI inspection and rehabilitation programmes. A number of different methodologies can be employed in order to mitigate CUI. The section will depend on the scale of any CUI, resources employed and location or type of plant being considered.

- Individual targeted high safety, health and environment (SHE) risk equipment with known CUI issues.
- Individual targeted high-economic-risk equipment with known CUI issues.
- Individual high-risk equipment with potential CUI issues.
- High-risk equipment within a particular area (zone approach).

5.4.1 Evaluated risk level: high–extreme

1 100% removal of thermal insulation.
2 Complete visual inspection for corrosion and condition of coating as applicable (including dye penetrant or alternating current field measurement (ACFM) inspection to check for Cl-ESCC of austenitic stainless steels) .
3 Evaluation of corroded areas by pit gauge, ultrasonic testing or radiography.
4 Analysis for root cause considering critical points.
5 Reinstatement of use of practices recommended in this document.
6 Re-evaluation of the risk.

5.4.2 Evaluated risk level: medium–high

1 Greater than 40% removal of thermal insulation including all critical points and damaged areas.
2 Complete visual inspection of exposed areas for corrosion and condition of coating as applicable (including dye penetrant or ACFM inspection to check for Cl-ESCC of austenitic stainless steels).

3 Evaluation of corroded areas by pit gauge, ultrasonic testing or radiography.
4 Analysis for root cause considering critical points.
5 Reinstatement of use of practices recommended in this document.
6 Re-evaluation of the risk.

5.4.3 Evaluated risk level: medium

1 Greater than 20% removal of thermal insulation including all critical points and damaged areas.
2 Complete visual inspection of exposed areas for corrosion and condition of coating as applicable (including dye penetrant or ACFM inspection to check for Cl-ESCC of austenitic stainless steels).
3 Evaluation of corroded areas by pit gauge, ultrasonic testing or radiography.
4 Analysis for root cause considering critical points.
5 Reinstatement of use of practices recommended in this document.
6 Re-evaluation of the risk.

5.4.4 Evaluated risk level: low

1 Removal of thermal insulation at all critical points with evidence of damage.
2 Complete visual inspection of exposed areas for corrosion and condition of coating as applicable (including dye penetrant or ACFM inspection to check for Cl-ESCC of austenitic stainless steels).
3 Evaluation of corroded areas by pit gauge, ultrasonic testing or radiography.
4 Analysis for root cause considering critical points.
5 Reinstatement of use of practices recommended in this document.
6 Re-evaluation of the risk.

5.4.5 Evaluated risk level: negligible

No inspection is required when the evaluated risk level is negligible.

6
Non-destructive examination and testing screening techniques for corrosion-under-insulation

6.1 Non-destructive examination and testing techniques

The NDE and NDT techniques listed below can be used to detect CUI. A more comprehensive description of each technique is given in Appendix I.

- External visual inspection (with and without removal of insulation).
- Ultrasonic thickness measurement (with and without removal of insulation, through inspection openings).
- Profile radiography.
- Flash radiography.
- Real-time radiography (RTR).
- Guided-wave ultrasonic measurements.
- Pulsed-eddy-current technique.
- Digital radiography.
- Infrared thermography.
- Neutron backscattering.
- Dye penetrant testing.

The limitations, advantages and disadvantages of each technique are detailed in Table 6.1. A comprehensive review of non-destructive evaluation techniques has been carried out by MTI [1] in 1998. This document provides a very thorough review of all the non-intrusive inspection methods available at that time; a summary is shown in Table 6.2.

6.2 Reference

1. Materials Technology Institute, *MTI Project 118 Detection of Corrosion Through Insulation*, September 1998.

Table 6.1 Limitations, advantages and disadvantages of different NDE and NDT techniques for CUI

NDE or NDT Technique	Limitations	Advantages	Disadvantages	Comments
External visual inspection	Requires removal of insulation; 'strip off and inspect'	Can see the problem; positively identifies all areas of CUI Can apply a range of tools to quantify the problem Gives confidence	Expensive and requires other techniques to quantify metal loss Cannot directly measure remaining wall thickness	The most effective inspection method If insulation removed on a sample basis, may not strip off 'worst areas' and give false confidence
External visual inspection without removal of insulation	Generally carried out as a first pass and is usually limited by access Very easy to cut windows	Little cost for an initial evaluation	Only covers small areas; will only provide a guide to potential problem areas	Can be very effective for a first pass on an installation with a CUI programme Windows can be source of water ingress
Ultrasonic thickness measurement through inspection openings	Only a very small area is inspected	It gives remaining wall thickness. Note that ultrasonic thickness measurements can be very effective for general CUI when taken internally	It can be difficult to obtain readings on a corroded surface	Generally not used for CUI
Ultrasonic thickness measurement	Requires removal of insulation and limited by surface condition	It gives remaining wall thickness following external and internal corrosion	Can be difficult to obtain thickness readings on a corroded surface Generally requires surface grinding or brushing.	Used in conjunction with pit gauging

Table 6.1 Cont'd

NDE or NDT Technique	Limitations	Advantages	Disadvantages	Comments
Profile radiography	Unlikely to detect Cl-ESCC in stainless steels Typically only a single orientation is used, making it possible to miss localised thinning	Gives remaining wall thickness without removing insulation Can be applied whilst equipment is running Will reveal both internal and external corrosion thinning	Only for pipe wall in small sections SHE issues, test areas require barriers to restrict access The exposure source is usually iridium 192; cobalt 60 is used for pipes of heavier wall, but the mass is about 250 kg Generally slow and suitable for pipe size <8 in	One of the most effective methods, with very good results achieved Often used to evaluate the suitability of piping for insulation removal and grit blasting
Digital radiography	Does not detect Cl-ESCC in stainless steels Typically only a single orientation is used making it possible to miss localised thinning	As above Image management easier	Scaffolding required when using cobalt 60 for thick sections (heavy enclosures (about 250 kg)) More expensive than profile radiography	As above Provides greater flexibility when reviewing images Ongoing developments include small-controlled-area radiography, SafeRad, complementary metal–oxide–semiconductor, gamma-scan real-time radiography systems

Flash radiography	Set-up requires at least $1\frac{1}{2}$ days It is utilised up to 1 m in diameter This technique does not detect SCC in stainless steels	Film processing generally takes about 15 min No need to remove insulation	Contrast and resolution are not as good as those for conventional radiography It can also be difficult to separate images from multiple exposures	
Real-time radiography (Lixi profiler)	Does not detect Cl-ESCC in stainless steels Thickness variations confuse interpretation	No requirement to remove insulation Fast and reliable survey method without need to remove insulation Gamma-ray method can give indication of remaining wall thickness Can be applied whilst equipment is running	Radiography gives only the profile of the outside pipe SHE issues, use of gamma-ray source test areas require barriers to restrict access, it gives video images that can be recorded for evaluation later Requires a considerable amount of manipulation to ensure adequate coverage	Technique shows promise although application slower than claimed
Real-time radiography (Image Scope)	Limited to small-bore connections	No requirement to remove insulation	Only provides profile of pipe outside diameter Requires a considerable amount of manipulation to ensure adequate coverage	Technique shows promise although application slower than claimed

Table 6.1 Cont'd

NDE or NDT Technique	Limitations	Advantages	Disadvantages	Comments
Guided-wave ultrasonic measurements	Does not detect localised corrosion and gives percentage wall thickness loss; only used for piping systems This technique does not detect SCC in stainless steels	The probe ring is applied at large intervals of pipe (6–10 m) and the measurement itself is a matter of minutes compared with the total inspection time Can be applied whilst equipment is running	Necessary to remove insulation where the probe ring must be applied (about 200 mm) It is utilised only for pipelines; not used for vessel or tanks Results distorted by the diameter of the test component	Very expensive Non-invasive technique
Pulsed-eddy-current technique	Does not detect localised corrosion including Cl-ESCC in stainless steels The inspection area is limited Does not work through galvanised steel cladding	Does not need to make contact with the surface Scaffolding can be reduced by using rope access or by attaching the measuring sensor to a straight pole Can be applied whilst equipment is running	Utilised for ferrous pipe, vessels or tanks Results distorted by the diameter of the test component	Requires validation

Infrared thermography	Does not detect CUI	Provides temperature information to detect the presence of moisture or water in insulation Can be applied whilst equipment is running	Must be utilised with another NDE or NDT system to verify CUI	Used as a screening tool Developments ongoing using pulsed techniques
Neutron backscattering	Does not detect CUI	Provides accurate information on the presence of moisture or water on insulation Can be applied whilst equipment is running	Must be utilised with another NDE or NDT system to verify CUI	Moisture measurement relative
Dye penetrant testing following removal of insulation	Requires removal of insulation and any protective coating	Gives indications of pitting or surface-breaking SCC	Very slow Mainly used for austenitic stainless steel Surface condition dependent; may not always detect fine cracking on heavily corroded surfaces	Prevention is the preferred solution for CI-ESCC

Table 6.2 Overview of capabilities and limitations of methods demonstrated during MTI Project 118

	Radiation						Electromagnetic		Ultrasonic		
	Tangential			Through transmission			Pulsed eddy current	Encircling coils	Single L modes	Multiple L modes	SH modes
	Neutron	Gamma	X-ray	Film digitising	Solid-state detector	Profiling					
Wet insulation effects	Severe	Some	Some	Some	Some	Some	None	None	Some	Some	None
Effect of pipe being water filled	Severe	Some	Some	Some	Some	Some	None	None	Some	Some	None
Inspect elbows?*	P	Y	Y	Y	N†	Y	P	N	N	N	N
Inspect vertical pipe?*	Y	Y	Y	Y	N	Y	Y	N	Y	Y	Y
Inspect under hangers?*	N	N	N	N	N	N	N	N	Y	Y	Y
Inspect across penetrations?*	P	Y	Y	P	N	N	N	N	P	P	P
Detect discrete defects?*	N	N	N	Unknown	Y	Unknown	N	Y	Y	Y	Y
Detect wall thinning?*	N	N	N	Unknown	Y	Y	Y	Y	Y	Y	N
Detect outside-diameter damage?*	N	Y	Y	Unknown	Y	Y	Y	Y	Y	Y	N
Detect inside-diameter damage?*	N	N	N	Unknown	Y	Unknown	Y	Y	Y	Y	Y
Inspect stainless steel pipe?*	Y	Y	Y	Y	Y	Y	N	N	Y	Y	Y
Inspect through galvanised jacket?*	Y	Y	Y	Y	Y	Y	P	P	Y	Y	Y
Inspect through stainless steel jacket?*	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Inspect across wires or straps?*	Y	Y	Y	Y	Y	Y	Y	P	Y	Y	Y
Pipe inspected (ft/ 8 h day)‡	500	500	500	20	250	1000	90	120	80	60	60
Operator skill§	B	I	I	I	I	I	B	A	A	A	A
Development‖	C	C	C	C	C	A	A	E	A	E	E
Type of method¶	L	S	S	L	S	S	L	S	G	G	G
Surface access required*	N	N	N	N	N	N	N	N	Y	Y	Y

* Y, method can achieve; N, method cannot achieve; P, method can partially achieve.
† A two-dimensional array of these detectors is now available for film-style through-transmission radiography, and robotic improvements are under way to allow inspection of vertical pipes and elbows.
‡ This is only an estimate and is only for the test stand used in this programme. Many methods will inspect more pipes with fewer penetrations and bends. Set-up time for the relatively short amount of pipe in the test stand also consists of a larger portion of time than if thousands of feet were to be inspected. The amount of pipe inspected in the field will be different. The field-ready techniques are typically faster than the emerging technologies. Some methods will be misrepresented because they are spot measurements that were used to perform full-body scanning.
§ B, basic (high-school and on-job training); I, intermediate (e.g. level II equivalent), A, advanced (Bachelor's degree or higher).
‖ C, commercially available; A, advanced stage of field testing, commercial very soon; E, entry level field testing.
¶ L, local; S, scanning; G, global.

7 Recommended best practice to mitigate corrosion-under-insulation

7.1 Background

In order to ensure that the field implementation of a best-practice insulation specification is successful, care must be taken in the development and design of all components of the specification. Deficiencies in any one of the components can and do lead to premature failure of the insulation system.

What are the primary parameters that control the effectiveness of an insulation system? What is the key parameter that controls life expectancy?

7.1.1 Key parameters

Field experience from a wide variety of oil, gas and petrochemical companies has indicated that the following parameters are important.

- Insulation selection.
- Protective coating selection.
- Weather barrier selection and design.
- Service temperatures ('cold' or 'hot' insulation).
- Local environment.
- Equipment and piping insulation design details.
- Installation procedures.
- Inspection and maintenance practices.
- Life cycle costs (LCCs).

Historically, greater emphasis has been placed on the type of protective coating, type of insulation and type of weather barrier to be selected with less emphasis on the installation and maintenance of the insulation system. Failure of the insulation system is relative. Often the weather barrier is the first to fail, followed by gradual degradation of the insulation and the protective coating, leading to hidden localised corrosion of the steel equipment beneath the insulation.

7.1.2 Assumptions

How is failure defined?

Failure is relative since it is associated with a number of components in a multicomponent system. It is often assumed that the weather barrier is impermeable to water ingress. This is not always the case. The external weather protective claddings are not intrinsically waterproof and so it should be assumed that water can penetrate the external weather barrier immediately after installation.

A second assumption is that the insulation cannot and does not 'hold' water. This again is not necessarily true because the extent of water retention is a function of the type of insulation being used; water can be retained by all insulation systems. CUI has been associated with all the different types of insulation materials that have been employed.

A third assumption is that the protective coating employed resists aqueous corrosion; again this is not always true. The life expectancy of coatings ranges from 2 to 25 years (and even greater in some circumstances) with an average expectancy of less than 10 years.

For the majority of the oil, gas and petrochemical companies, failure is usually defined when leakage to the atmosphere occurs as a result of metal perforation.

The above assumptions are true for carbon steel installations. Cl-ESCC of austenitic stainless steels, although less typical, is another failure definition.

7.2 Current corrosion-under-insulation prevention methods

It is the current oil, gas and petrochemical practice to include most of or all the following conventional CUI mitigation methods.

- Design and install the insulation system to exclude water ingress.
- Application of a suitable organic protective coating to resist corrosion.
- Perform periodic inspection and non-destructive inspection (NDE and NDT) activities.
- Periodically strip all insulation, prepare surfaces for coating and reinsulate.
  - Maintenance of a conventional coating system (paint) is the only mitigation for CUI on carbon steel equipment.
  - Conventional paint systems have an average life expectancy (9–13 years) [1] that is heavily dependent on proper surface preparation and application.
  - Cold service equipment prevents maintenance of conventional paint systems without unit shutdowns.

7.3 How to achieve a life expectancy of over 25 years

The rate of corrosion is influenced by the service conditions, the local environment and by the design details. The rate of corrosion is also influenced by the installation practices and by the local inspection and maintenance practices. These all affect the total cost of the installation (i.e. the LCCs).

So what is the key parameter that controls the life expectancy of an insulation system and what is required to ensure a life expectancy in excess of over 25 years?

It is now believed that the key parameter that controls the life expectancy of an insulated system is the protective coating. Failure of the weather barrier due to inadequate design or installation will lead to water ingress and retention. Subsequent degradation of the barrier coating leads to corrosion. The selection of a coating is therefore the key to the success of the insulation system as a whole. Many types of coating system are available but the selection criteria must include the following in order to be economically viable and effective [1].

- *The lifetime of the equipment*. Include both the internal and the external corrosion mechanism and corrosion rates. Typically a plant life expectancy in excess of 25 years for equipment is generally used as the basis for all economic evaluations. Consideration of shorter periods can be adopted when the remnant plant life is limited. The majority of refining equipment in use today is considerably older than 25 years as essential refineries were initially installed during the 1950s and 1960s. Construction of petrochemical, gas and hydrocarbon processing plants and offshore production facilities continue, however, to the present day.
- *The cost of application and reapplication of the protective coating and insulation system over the lifetime of the equipment*.
- *The expected lifetime of the protective coating system*. This has consistently fallen short of all expectations.

Appendix C provides more information on the many types of protective coating that are available; however, the coating that is most likely to provide effective corrosion protection for over 25 years is thermally sprayed aluminium (TSA). It is therefore recommended that, where a minimum design life of 25 years is required, TSA should be considered for the protective coating of all new equipment and should always be considered for the protective coating of equipment subject to maintenance and rehabilitation work. The following sections provide more detail on the benefits of TSA which will provide a low-cost leak-free system for well over 25 years. The application of conventional paint systems have a life expectancy heavily dependent on proper surface preparation and application (Table 7.1).

Table 7.1 CUI prevention online field application: TSA and paint

Features	TSA	Conventional paint
CUI protection	25–30 years; maintenance free; inspection free	5–13 years; tends to low side for online application
Protection in cyclic service	Yes	No effective paint system
Upper continuous operating temperature	480 °C (if a seal coat is not applied)	Typically 175 °C (up to 540 °C with specialist paint systems)
Schedule impact	None; one-coat application (if a seal coat is applied, then same cure required as for paint)	24 h typically; multiple coats required
Environmental impact	None (for seal coat, same as paint)	Must meet volatile organic compounds and disposal regulations
In-place cost ratio	1.05–1.20	1.0
Durability	Very resistant to mechanical abuse Minor damage does not result in CUI	Very susceptible to mechanical abuse Any damage results in CUI
Required surface preparation	Sa $2\frac{1}{2}$ (near white)	Sa $2\frac{1}{2}$ (near white)
Application method(s)	Twin-arc spay or flame spray (for seal coat, as for paint)	Spray, brush and roller
Application accessibility	Arc or spray head to within an angle of 30° normal to surface	Brush or roll for restricted access but life decreases
Temperature limit for application	None but service must be dry unless applying seal coat	Ambient to about 60 °C
Work permit required	Hot work	Cold work, but it can restrict hot work in the area where painting is taking place

7.3.1 Corrosion-under-insulation preventive measures: recent approaches

The following CUI prevention or mitigation strategies have been developed in order to prolong the life of all insulated equipment. They maintain a lower failure potential over a longer life cycle and are, therefore, not as dependent on the effective but expensive maintenance and inspection activities that are required to manage CUI.

- Application of TSA coating system.
- Upgrading to stainless steel when economically justified.
- Removing unnecessary insulation.
- Removing insulation at pipe support vents, etc., with a seal either side to remove the water ingress point.
- Use of aluminium foil to prevent Cl-ESCC.
- Use of waterproof and impervious non-metallic weather protection barriers.

7.3.2 Material upgrade possibilities

The methodologies for CUI mitigation include the following.

- Painting or coating carbon and austenitic stainless steel for protection.
- Application of TSA.
- A metallurgy upgrade from carbon–manganese steel to an austenitic or duplex stainless steel.

Whilst CUI of carbon steel is a relatively slow process, austenitic stainless steels are susceptible to accelerated corrosion (particularly Cl-ESCC) if exposed to wet aqueous conditions containing chlorides. Failures of insulated austenitic stainless steels by pitting and SCC due to chlorides have been extensively reported. Duplex stainless steels are less susceptible but are not totally immune. However, provided that suitable precautions are taken (especially when considering cold service insulation), stainless steels can prove to be more economical than carbon steels if LCCs are considered.

In order to minimise the risk of chloride SCC, the use of duplex stainless steels should be considered for operating temperatures greater than 50 ºC .The upper temperature limit at which duplex stainless steels can be used will depend on the actual grade selected. A temperature of 120 ºC is typically used for the generic 2205 duplex stainless steel. Each application must be carefully reviewed by the appropriate specialist engineers before proceeding. The greatest savings can be made for the following.

- Small-diameter piping systems.
- Equipment requiring cold service insulation.
- Equipment that will be operating under cyclic conditions.
- Equipment that will be operating in high-humidity environments.

Since it will often be possible to reduce or eliminate corrosion allowances when moving from carbon steel to stainless steel, significant savings can often be made in terms of total weight and cost by specifying thinner

Table 7.2 Allowable stress comparison [2]

	Piping of nominal 1 in diameter (barg (klbf/in^2))	Piping of nominal 2 in diameter (barg (klbf/in^2))	Piping of nominal 3 in diameter (barg (klbf/in^2))
TP304L Sch40S	219 (3.18)	137 (1.98)	130 (1.88)
TP304 Sch40S	263 (3.81)	163 (2.37)	155 (2.25)
SAF 2304 Sch10S	296 (4.29)	159 (2.31)	118 (1.71)
SAF 2205 Sch10S	319 (4.62)	171 (2.49)	127 (1.84)
SAF 2507 Sch10S	372 (5.39)	200 (2.90)	148 (2.15)

schedules. Although duplex stainless steels have a greater cost than austenitic stainless steels, advantage can be taken of the higher mechanical properties of duplex stainless steels in order to reduce the thickness of equipment further.

This can be illustrated by considering piping purchased according to ASTM A312/A79 and calculating the maximum allowed pressure at 90 ºC (200 ºF) according to ASME B31.3. Table 7.2 [2] shows how the allowable pressure increases as the grades of stainless material is increased.

For an application that would require a Sch40S type 304 stainless steel piping to contain the design pressure, a Sch10S duplex stainless steel pipe would most probably suffice. Obviously, calculations based on the actual design parameters need to be carried out. These should also include other factors such as piping stresses, etc.

Pipe thickness reduction not only will save on direct material cost but also will lead to lower costs and savings when considering the following.

- Welding (i.e. lower labour, less supervision and lower welding material costs).
- Lower total weight (i.e. lower cost for scaffolding, handling, etc.).
- Indirect savings due to lower instances of leaks.
- Safer operation.

Not every application will show an economic incentive. The costs depend on the availability of the material, the process environment, operating temperature, etc. However, the LCC principle should be used to determine the actual impact on overall costs of a project and not only on the initial installation costs alone.

7.4 Benefits of thermally sprayed aluminuim

The cost of a protective coating system that is being applied beneath an insulation system should include the total cost of installation and the total costs involved in the maintenance and inspection of the system over the entire life of the system.

The main advantages of TSA coatings over conventional organic coatings include the following.

- Longer life expectancy with minimal requirements for maintenance and inspection.
- Resistance to mechanical damage.
- Greater range of temperature resistance than organic coatings (from –100 ºC to 500 ºC).
- Provides sacrificial protection to steels in aqueous environments.

The main disadvantages of TSA coatings over conventional organic coating include the following.

- Higher cost of application.
- Increased difficulty of field application.
- Resistance to change by operations and maintenance organisations.

On balance, providing that the total LCCs of operating a piece of insulated equipment are taken into consideration, the application of TSA, as a protective corrosion-resistant coating can be more effective and more economic than using an organic coating. The costs that should be included are as follows.

- Cost of surface preparation.
- Cost of coating application.
- Cost of field erection (if new equipment) or extra costs if field applied.
- Cost of inspection and quality assurance.
- Cost of in-service inspection.
- Cost of in-service maintenance.
- Cost of repair and/or replacement in the event of CUI.

7.5 Use of personnel protective guards

Removal of insulation stops CUI and the associated inspection and maintenance costs. With the use of personnel protective guards (see Appendix H) instead of insulation, savings of up to 100% of the costs associated with CUI incidents which can help to recover quickly the installation cost of the personal protection guards.

Traditionally personal protection consists of insulating the pipework to prevent human contact with hot surfaces. This is an easy option and is predominately applied because other methods are seen as more expensive and requiring more resources. With business needs driving efficiency improvements in maintenance and capital spending, the initial cost of personal protection is as important a factor as LCCs. Use of personal protection guidelines will reduce initial costs as well as improve life cycle savings.

Possible savings include the following.

- 100% of the cost of CUI (pipe replacement, painting and insulation).
- 10–20% on initial costs compared with thermal insulation.
- 90% or more on future pipe inspection costs.

A number of UK and European standards are available [3, 4], which give more detailed guidance for the design of guarding for personnel protection against heat exposure. They are utilised for equipment or pipelines whose surface temperature is above 60 ºC. Each guard should be individually designed to duty and local service conditions.

- Guards and their supports shall be manufactured from carbon steel, which may be galvanised or painted. (The mesh may be painted with yellow stripes, 50 mm wide, and shall include a hazard sign indicating 'Hot surface'.)
- The guard mesh shall be 12 mm square when the distance from the heat source is less than 40 mm and can be a maximum of 40 mm square when the distance from the heat source is greater than 180 mm. The guards shall extend to a height of not more than 2 m above or 600 mm beyond areas at ground level or on platforms, access ways, stairways, ladders and other positions of personnel access for operational purposes.
- Guards may be supported by the pipeline or equipment that they are protecting. They shall have the support clamp(s) painted with same paint system as that specified for the pipeline.
- Guards shall be securely anchored and not distort if lent against. They shall be free from sharp edges.
- All guarding shall be of a permanent type, designed to withstand mechanical abuse.

7.6 Use of aluminium foil to mitigate chloride external stress corrosion cracking of austenitic stainless steel

As discussed earlier, the first reported instance of Cl-ESCC on austenitic stainless steel was published in 1965 [5]. Since then many articles have been published reporting similar instances but without guidance on how to mitigate the problems. Many companies and contractors currently use aluminium foil to prevent Cl-ESCC of austenitic stainless steel piping and vessels. The use of aluminium foil to mitigate Cl-ESCC was first published by ICI in 1985 [6]. When applied as recommended it has been shown to be 100%

Table 7.3 Comparison chart, aluminium foil versus conventional painting for CUI protection on insulated austenitic stainless steel piping and vessels

Feature	Aluminium foil	Conventional paint
Corrosion protection for equipment operating in the ambient to moderate temperature range	25–30 years based on ICI reported experience	9–13 years maximum depending on environment (dry)
High temperature > 190 °C (350 °F) cyclic service corrosion protection	No decrease in service life	No effective paint system exists
Upper temperature limit	540 °C (1000 °F) dry	150–230 °C (300–450 °F)*
Chemical resistance	Resistant to all solvents, but narrower pH resistance range (not resistant to strong acids or bases)	Wide pH resistance range, but not resistant to solvents
Cure time between coatings	None	Approximately 24 h between coatings
Environmental impact	None	Must meet volatile organic compounds and disposal regulations
Application cost for piping (painted carbon–manganese steel equal to 1)	1.26 (nominal pipe size, 2 in) 1.54 (nominal pipe size, 4 in) 2.69 (nominal pipe size, 8 in)	2.07 (nominal pipe size, 2 in) 2.76 (nominal pipe size, 4 in) 4.79 (nominal pipe size, 8 in)
Durability	Excellent; minor damage will not result in corrosion	Very susceptible to mechanical abuse. Any damage to coating will result in corrosion
Required surface preparation	None†	Sa $2\frac{1}{2}$ or better
Application method(s)	Overlapping wrap of aluminium foil	Spray, brush and roller
Application accessibility	Same as for insulation	Able to apply to surfaces with restricted access using brushes and rollers
Work permit required	Cold work	Cold work, but it can restrict hot work in the area where painting is taking place

* Typical for most coatings; silicon-based heat-resistant coatings with upper temperature limits of 540 °C are available.
† Power water wash or solvent degrease may be needed if surface contains lubricants, grease, dirt or organic residue.

effective in preventing CUI due to Cl-ESCC. Concern over possible liquid-metal cracking of austenitic stainless steels has been expressed; however, a literature search did not highlight any instances in which aluminium causes the initiation of liquid-metal cracking. Cost comparisons in both North America [7] and Europe showed that the cost of aluminium-foil wrapping was 60–80% of the conventional coating cost. Discounted cash flows (DFCs) of 40% or greater will be typical.

The use of aluminium foil is recommended for all austenitic stainless steel piping requiring CUI Cl-ESCC protection on all maintenance and capital projects [8]. Typically, austenitic stainless steels can be used economically for small-bore piping replacing small-bore carbon steel piping failing from CUI. Aluminium foil can also be used on austenitic stainless steel vessels in lieu of conventional coating for Cl-ESCC cracking protection; costs should be economically based (Table 7.3).

Aluminium foil should *not* be used in sweating service because the service life of aluminium foil will be shortened. TSA is recommended in sweating service.

7.7 References

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8 Design for the prevention of corrosion-under-insulation

8.1 Introduction

Equipment and piping design has an important influence on CUI. If proper consideration is given to CUI at the design stage it may be possible to eliminate corrosion altogether, or at least to limit significantly the potential for CUI and Cl-ESCC. It is the intention of this chapter to give a brief overview of what designers should consider and some examples of good design practices that will reduce the potential for CUI and Cl-ESCC.

It is not the intention here to provide an in-depth detailed description of all design aspects relating to CUI prevention. Reference can be made to the *CINI Manual, Insulation for Industries* [1], for explicit details relating to insulation design.

There is some overlap with other sections of these guidelines, particularly regarding materials used for insulation, weatherproofing and coating, and using life cycle costing. The reader is therefore recommended to refer to these other sections for additional information.

8.2 Challenge the requirement for insulation

The best way of avoiding CUI is not to fit insulation at all. Section 4.3 provides detailed information on how the need for insulation can be challenged. Ideally this decision should be correctly made at the design stage. Insulation is required for many reasons such as process requirements, heat conservation, fire protection, noise, preventing freezing or condensation, and personal protection. However, experience has shown that sometimes the level of challenge has not been sufficient when deciding whether insulation is required and this has resulted in insulation being fitted when it need not have been. Where insulation is required only for personal protection it is better to fit metal guards rather than insulation.

8.3 Plant layout

When designing where to situate equipment and piping, consideration should be given to providing sufficient space to allow effective inspection and maintenance in the plant. For example, experience has shown that pipes placed too close together on the plant are practically impossible to inspect and maintain effectively.

8.4 Mechanical considerations: equipment and tanks

Equipment and tank design and mechanical details have important influences on the potential for CUI. There are many undesirable design features that influence CUI, some of which are as follows.

- Using shapes that are likely to retain water, such as flat horizontal surfaces, vacuum rings and insulation support rings.
- Using shapes that are impractical to insulate and weatherproof effectively, such as gussets and I-beams.
- Using shapes that funnel water into the insulation, such as angle-iron brackets.
- Other items that cause interruption in the weatherproofing, such as lifting lugs, ladder brackets, nozzle extensions, decking and platform supports.

The more breaks that there are in the weatherproofing, the more likely it will be that water will enter the insulation and potentially cause CUI. It is therefore essential to minimise the number of nozzles, supports and fixings that will protrude through the weatherproofing. Because of the difficulty in weatherproofing and sealing vessel lifting brackets, it has become good practice to cut these off once the equipment has been lifted on to the plant and securely fixed in position.

Some further examples of good practice include the following.

- Hand railings on insulated tank roofs should be installed at the side of the roof edge instead of on top of it.
- Fixings on insulated tank walls and roofs should be cylindrical rather than angle steel, to avoid retention of water.
- Angle steel used for vacuum rings on columns should be installed with the outer vertical edge downwards to allow water to drain off.
- Nameplates on insulated equipment should not interfere with the insulation and weatherproofing; they should be fitted on short brackets so that the nameplate does not extend beyond the weatherproofing. A duplicate nameplate can be mounted on the outside of the metal jacketing for in-service identification.

8.5 Mechanical considerations: piping

As for equipment and tanks, the more breaks that there are in the weatherproofing, the more likely it will be that water will enter the insulation and potentially cause CUI. It is therefore essential to minimise the number of vents, drains, supports, flanges and fixings that will protrude through the weatherproofing.

Pipe supports are a common area for CUI, owing to the difficulty in insulating and sealing around them properly. Rod hanger or clamps used to support piping by 'direct contact' are impractical to insulate and seal effectively against water ingress. Another support that is similarly difficult to insulate is the flat beam support, where the piping directly rests on a flat metal beam.

All insulated piping should therefore be designed with suitable pipe supports that mitigate, or at least minimise, water ingress. It is considered good practice to use high-density insulation at support locations and to fit load-bearing supports that will contact the weatherproofing only, thus resulting in a continuous weather barrier.

Some examples of further good practice include the following.

- Locating valves and flanges in the horizontal part of piping runs rather than the vertical to limit water retention.
- Providing enough space between piping and adjacent piping or plant structural supports to enable effective inspection and maintenance *in situ*.
- Not placing insulated piping in trenches or drains below grade because of the potential for immersion in water if the drains are not kept clear.
- Avoiding clamped pipe shoes in critical CUI areas and using only welded shoes to avoid points of entrapment.
- Not insulating vertical pipe supports, vents, etc., and seal of insulation either side.

8.6 Materials of construction

Carbon steels and low-alloy steels are the most common materials of construction for equipment, tanks and piping. When insulated, these materials often suffer from CUI in the form of localised or general corrosion. The potential for CUI is influenced by several factors including the operating temperature and the potential for water ingress into the insulation. If the risk of CUI is considered very high for, say, carbon steel, the designer may select another material of construction that will not suffer from CUI (e.g. austenitic and duplex stainless steels, accepting that there may still be a risk of Cl-ESCC). The designer may even select high-nickel alloy materials that are almost immune to both CUI and Cl-ESCC.

Naturally, when selecting more costly materials of construction at the design stage it is important to consider life cycle costing over the design life of the project, to provide economic justification for selecting these materials.

8.7 Coatings and wrappings

Coatings and wrappings applied to the external surface of equipment, tanks and piping are the last line of defence in preventing CUI. Generally speaking, organic coatings, TSA coatings and aluminium wrapping are most commonly used to reduce the potential for CUI.

8.7.1 Organic coatings

Organic coatings need to be of high-quality immersion grade to provide a barrier to CUI. Some provide good protection for many years. However, there is also poor experience where water ingress into the insulation has caused premature coating breakdown and significant CUI. Organic coatings applied with good quality control procedures are normally considered to have a lifetime of 9–13 years before routine inspection and maintenance is required.

8.7.2 Thermally sprayed aluminium coatings

Historically, TSA coatings have been less commonly applied than organic coatings. TSA coatings have been applied to carbon steel equipment to provide a barrier to CUI. Experience has shown that they perform remarkably well with lifetimes of 20–30 years [2] before first inspection and maintenance are required. It is important to consider life cycle costing at the design stage when considering TSA coatings instead of organic coatings.

8.7.3 Aluminium wrapping

Aluminium wrapping has most often been applied to insulated austenitic stainless steel equipment and piping to limit the potential for Cl-ESCC. Experience has shown that organic coatings do not necessarily provide an effective barrier to Cl-ESCC. There is good experience within industry that aluminium foil wrapping has provided a more effective solution than using organic coating by acting as both a physical barrier and a galvanic barrier to preventing Cl-ESCC. Care must be taken to ensure that the external insulation weather cladding is correctly applied under the control of appropriate quality assurance levels.

8.8 Insulation

Poorly designed or applied insulation systems can result in water ingress into the insulation or condensation of water from atmospheric moisture, leading to CUI. The underlying metal also corrodes when insulation becomes wet following the breakdown of weatherproofing or vapour barrier after equipment and piping is put into service and is exposed to the weather without a corrective maintenance programme. Insulation system life can be prolonged, and substrate metal corrosion can be reduced, by better design of protrusions, attachments, supports, drainage points and expansion–contraction joints.

Generally, industrial insulations fall into two categories: low-temperature (below ambient) and high-temperature (above ambient) applications.

Low-temperature insulation typically includes polyurethane, polyisocyanurate, flexible elastomeric foams, cellular glass and phenolics. These insulation types normally require a vapour barrier under the outer weatherproofing to minimise the potential for condensation of atmospheric moisture.

High-temperature insulation typically includes perlite, calcium silicate, mineral wool, cellular glass and fibreglass. For SHE reasons the use of asbestos is no longer specified for new construction.

System movement must be allowed for in insulation design. Rigid and semirigid insulation may require expansion joints and failure to install these can result in uncontrolled movement of the insulation in relation to the equipment or piping. This may result in vapour barrier or weatherproofing breakdown and condensation or ingress of water into the insulation.

Thermal movement caused by for example piping expansion or contraction must also be addressed. The linear coefficients of thermal expansion of both the piping and the insulation must be considered. The difference between the amount of pipe and insulation movement, together with routing considerations, normally determines how many expansion–contraction joints are needed in the insulation. Expansion–contraction joints are typically constructed in staggered layers to avoid a path for water ingress.

Insulation that minimises water ingress and does not retain water can effectively act as a barrier to CUI. Therefore the 'closed-cell' insulation materials (e.g. flexible elastomeric foams and cellular glass) can provide a more effective barrier to water ingress than 'open-cell' insulation materials (e.g. mineral wool and calcium silicate).

In addition to water absorbency, another factor to consider is the chemical content of the insulation. It should be inert, containing no chemicals that would contribute to corrosion or Cl-SCC. Some industrial companies specify a leachable chloride content of less than 10 mg/kg as a way of minimising the potential for Cl-SCC of insulated austenitic stainless steels.

A more recent insulation design which has proven successful is 'non-contact insulation'. This design has an air gap between the equipment surface and the insulation. The insulation contacts a mesh screen that is raised above the equipment surface; hence any ingress of water into the insulation does not contact the equipment to cause corrosion damage. The air gap enables the equipment surface to stay relatively dry and also allows insertion of a boroscope inspection tool to check the external condition of the equipment, without removing the insulation and weatherproofing.

Where there are load-bearing supports (e.g. clamp type) it is good practice to use high-density insulation so that supports can be fitted to the outer weatherproofing and an area for water ingress is not created. Additionally, high-density insulation is recommended at areas of high foot traffic so that, if the weatherproofing is walked on, it is not easily damaged.

8.9 Weatherproofing

Weatherproofing provides mechanical and weather protection for insulation systems. Although weatherproofing acts as a barrier to CUI, it is susceptible to weather, chemical attack and foot traffic damage once it is installed; therefore it should be adequately maintained.

Insulation weatherproofing materials basically come in two forms: metallic and non-metallic. The most common metallic weatherproofing materials are aluminised steel, galvanised steel, aluminium and stainless steel. Common non-metallic weatherproofing materials are ultraviolet-curable glass-reinforced plastics, polymeric compounds, coated tapes and cements.

Metal weatherproofing materials tend to become damaged easily if walked on and this increases the potential for water ingress into the insulation. The use of ultraviolet-curable glass-reinforced plastic weatherproofing provides a more robust barrier that can support foot traffic without becoming damaged.

The choice of weatherproofing should consider several factors for example, an assessment of LCCs, the complexity of the equipment/piping, how much foot traffic is expected and the temperature of the substrate.

The design of weatherproofing needs to take into consideration system movement and thermal expansion–contraction. Metal weatherproofing joints and protrusions are normally sealed with mastic or silicone materials to reduce the potential for water ingress. However, these sealants cannot be relied upon since they weather and break down. It has proven much better to overlap joints and to fit weatherproof plates around protrusions to minimise the potential for water ingress.

Weatherproofing should be designed so that it is water repellent and it does not allow water retention. An example of this is metal weatherproofing that is sloped at column vacuum rings and insulation support rings. Significant experience shows that using flat weatherproofing at these locations has resulted in water ingress and CUI of the column wall above the vacuum or insulation support ring.

Weatherproofing attachment methods should be compatible with the equipment and piping operating temperatures, particularly where the insulation terminates (e.g. at flanges). Using screws in metal weatherproofing on cold insulation systems may result in puncturing of the protective vapour barrier.

8.10 References

1. *CINI Manual, Insulation for Industries*, Spijkernisse, Stichting Commissie Isolatie Nederlanse Industrie (CINI), 2006.
2. K.P. Fischer, W.H. Thomason, T. Rosbrook and J. Murali, 'Performance of thermal-sprayed aluminum coatings in offshore service', *Mater. Performance*, 1995, **34**(4), 27–34.

9
Appendix overview

In order to streamline these guidelines, additional information concerning the management and mitigation of CUI is attached in the form of appendixes. These contain additional information that is more detailed in nature and provides a basis for the preparation of individual company inspection and CUI management procedures or supplement existing procedures. The information is not proprietary in nature and can be used immediately. It is hoped that additional information will be added in future revisions of the guidelines that will continue to help with eliminating CUI.

Appendix A
Cost-economic evaluation

Although application of TSA is known to be an effective mitigation strategy for CUI, the initial capital or refurbishment costs tend to be higher than the costs for applying conventional organic coatings. In order to show that it is economically beneficial to apply TSA as an alternative to organic coatings, plant management needs a positive economic evaluation to show that the long-term costs of TSA are actually lower than the costs of conventional organic coatings. The simplest method to show this is to determine the LCCs and to calculate a DCF.

The LCC determination includes the following.

- Lifetime cost of acquisition.
- Total erected cost, namely the sum of all the direct and indirect costs to install insulation on piping or equipment, including the cost of access (scaffolding), surface preparation, insulation and insulation cladding, coating costs and installation.
- Total erected cost of any piping that needs replacement.
- Lifetime support cost.
    - The total cost of resources and yearly costs for operation and maintenance.
- Lifetime unavailability cost.
    - The sum of yearly costs due to unavailability of system and loss of earnings.

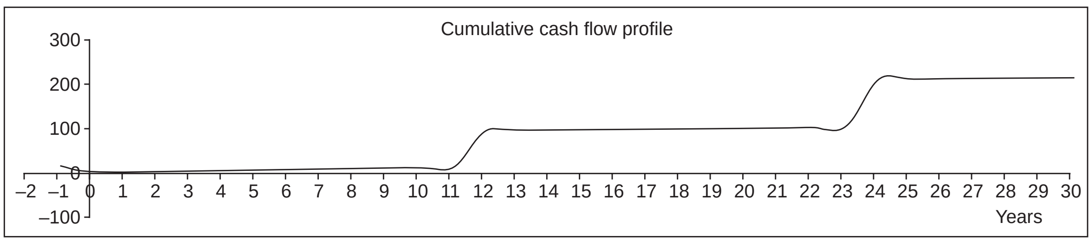
Life cycle savings are inherent in the use of TSA and can be very significant. Many large organisations have their own in-house methodologies to determine the LCC and DCF for project evaluations. However, the analysis can be easily performed using a simple spreadsheet. Three examples are given in Fig. A.1(a), Fig. A.1(b) and Fig. A.1(c).

Figure A.1(a) shows the analysis for a small project with incremental cost of €2×10^4 for TSA (€1.2×10^5 versus €10^5) and includes recoating costs (DCF of 21.2% over 30 years), Fig. A.1(b) show the analysis for a project with an incremental cost of €10^5 for TSA compared with a

Example 1 — Example CUI Economics, TSA v Organic coating — Typical recoating cycle with interim inspection — Typical example of building up the revenue impacts (profit/expenses) to input to the cash flow analysis

		2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Inflation rate	2%																
TSA coating				−120													
Organic coating, repaint 12 yearly with interim inspection				−100	0	0	−2.5	0	−2.76	0	0	0	0	−3.05	0	−122	0
Net				−20	0	0	2.5	0	2.76	0	0	0	0	3.047	0	121.9	0
Currency units	kEuro				Revenue Start-up												
	Total	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Ref CBM-070-004		−2	−1	0	1	2	3	4	5	6	7	8	9	10	11	12	13
A Investment Capital		0	0	0	0												
B Associated Facilities	0			0													
C Future Capital Investment	0																
D Capital Equivalent of Lease	0																
E Working capital	0																
F Investment credits	0																
G Other	0																
H Total		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I Residual Value																	
J Gross Profit before NRE, D, T				−20	0	0	2.5	0	2.76	0	0	0	0	3.047	0	121.9	0
K Non-Recurring Expense	0			0													
Depreciation profile	15yr str line				0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067
Depreciation	−20				−1.33	−1.33	−1.33	−1.33	−1.33	−1.33	−1.33	−1.33	−1.33	−1.33	−1.33	−1.33	−1.33
Taxable income		0	0	−20	−1.33	−1.33	1.167	−1.33	1.427	−1.33	−1.33	−1.33	−1.33	1.714	−1.33	120.6	−1.33
L Income Tax	34%	0.0	0.0	6.8	0.5	0.5	−0.4	0.5	−0.5	0.5	0.5	0.5	0.5	−0.6	0.5	−41.0	0.5
M Net Cash Flow		0.0	0.0	−13.2	0 .5	0.5	2.1	0.5	2.3	0.5	0.5	0.5	0.5	2.5	0.5	80.9	0.5
N Net cash flow Alternate																	
O Net incremental cash Flow		0.0	0.0	−13.2	0.5	0.5	2.1	0.5	2.3	0.5	0.5	0.5	0.5	2.5	0.5	80.9	0.5
IRR or DCF	**21.2%**																
NPV	12.0%			**14**	kEuro												
Cum. cash flow profile		0.0	0.0	−13.2	−12.7	−12.3	−10.2	−9.7	−7.5	−7.0	−6.6	−6.1	−5.6	−3.2	−2.7	78.2	78.6

	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Inflation rate																	
TSA coating																	
Organic coating, repaint 12 yearly with interim inspection	0	−3.36	0	0	−3.57	0	0	0	−3.86	0	−160.84	0	0	−4.267	0	0	0
Net	0	3.365	0	0	3.571	0	0	0	3.865	0	160.844	0	0	4.2672	0	0	0
Currency units																	
	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Ref CBM-070-004	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
A Investment Capital																	
B Associated Facilities																	
C Future Capital Investment																	
D Capital Equivalent of Lease																	
E Working capital																	
F Investment credits																	
G Other																	
H Total	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I Residual Value																	
J Gross Profit before NRE, D, T	0	3.365	0	0	3.571	0	0	0	3.865	0	160.844	0	0	4.2672	0	0	0
K Non-Recurring Expense																	
Depreciation profile	0.067	0.067															
Depreciation	−1.33	−1.33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Taxable income	−1.33	2.031	0	0	3.571	0	0	0	3.865	0	160.844	0	0	4.2672	0	0	0
L Income Tax	0.5	−0.7	0.0	0.0	−1.2	0.0	0.0	0.0	−1.3	0.0	−54.7	0.0	0.0	−1.5	0.0	0.0	0.0
M Net Cash Flow	0.5	2.7	0.0	0.0	2.4	0.0	0.0	0.0	2.6	0.0	106.2	0.0	0.0	2.8	0.0	0.0	0.0
N Net cash flow Alternate																	
O Net incremental cash Flow	0.5	2.7	0.0	0.0	2.4	0.0	0.0	0.0	2.6	0.0	106.2	0.0	0.0	2.8	0.0	0.0	0.0
IRR or DCF																	
NPV																	
Cum. cash flow profile	79.1	81.8	81.8	81.8	84.1	84.1	84.1	84.1	86.7	86.7	192.8	192.8	192.8	195.6	195.6	195.6	195.6



(a)

A.1 Examples of the spreadsheets used for the cash flow analyses (NRE, non-recurring expenses; IRR, internal rate of return; DCF, discounted cash flow; NPV, net present value) for projects with incremental costs of (a) €2 × 10^4 (DCF of 21.2% over 30 years), (b) €10^5 (DCF of 26.0% over 30 years) and (c) €10^5 (DCF of 26.3% over 30 years). The tables show the cash flow analyses, i.e. the determination of the LCCs and DCFs. The figures show the cumulative cash flow profiles.

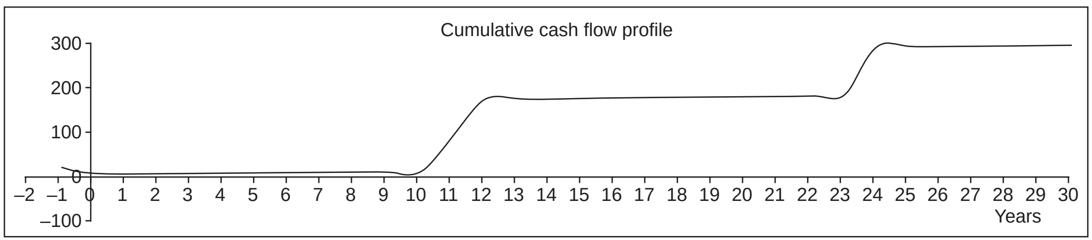
Example 1

Example CUI Economics — Typical recoating cycle with interim inspection – with cost of CUI incident

TSA v Organic coating — Typical example of building up the revenue impacts (profit/expenses) to input to the cash flow analysis

Inflation rate	2%																
TSA coating				–120													
Advanced NDE costs															–120		
Organic coating, repaint 12 yearly with interim inspection				–100	0	0	–2.5	0	–2.76	0	0	0	0	0	0	–121.9	0
Net				–20	0	0	2.5	0	2.76	0	0	0	0	0	120	121.9	0
Currency units	kEuro				Revenue Start-up												
	Total	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Ref CNM-070-004		–2	–1	0	1	2	3	4	5	6	7	8	9	10	11	12	13
A Investment Capital		0	0	0	0												
B Associated Facilities	0			0													
C Future Capital Investment	0																
D Capital Equivalent of Lease	0																
E Working capital	0																
F Investment credits	0																
G Other	0																
H Total		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I Residual Value																	
J Gross Profit before NRE, D, T				–20	0	0	2.5	0	2.76	0	0	0	0	0	120	121.9	0
K Non-Recurring Expense	0			0													
Depreciation profile	15yr str line				0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067
Depreciation	0				0	0	0	0	0	0	0	0	0	0	0	0	0
Taxable income		0	0	–20	0	0	2.5	0	2.76	0	0	0	0	0	120	121.9	0
L Income Tax	34%	0.0	0.0	6.8	0.0	0.0	–0.9	0.0	–0.9	0.0	0.0	0.0	0.0	0.0	–40.8	–41.4	0.0
M Net Cash Flow		0.0	0.0	–13.2	0.0	0.0	1.7	0.0	1.8	0.0	0.0	0.0	0.0	0.0	79.2	80.5	0.0
N Net cash flow Alternate																	
O Net incremental cash Flow		0.0	0.0	–13.2	0.0	0.0	1.7	0.0	1.8	0.0	0.0	0.0	0.0	0.0	79.2	80.5	0.0
IRR or DCF	**26.0%**																
NPV	12.0%			**33**	kEuro												
Cum. cash flow profile		0.0	0.0	–13.2	–13.2	–13.2	–11.6	–11.6	–9.7	–9.7	–9.7	–9.7	–9.7	–9.7	69.5	149.9	149.9

Inflation rate																	
TSA coating																	
Advanced NDE costs																	
Organic coating, repaint 12 yearly with interim inspection	0	–3.365	0	0	–3.571	0	0	0	–3.865	0	–160.8	0	0	–4.267	0	0	0
Net	0	3.365	0	0	3.571	0	0	0	3.865	0	160.8	0	0	4.267	0	0	0
Currency units																	
	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Ref CNM-070-004	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
A Investment Capital																	
B Associated Facilities																	
C Future Capital Investment																	
D Capital Equivalent of Lease																	
E Working capital																	
F Investment credits																	
G Other																	
H Total	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I Residual Value																	
J Gross Profit before NRE, D, T	0	3.365	0	0	3.571	0	0	0	3.865	0	160.8	0	0	4.267	0	0	0
K Non-Recurring Expense																	
Depreciation profile	0.067	0.067															
Depreciation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Taxable income	0	3.365	0	0	3.571	0	0	0	3.865	0	160.8	0	0	4.267	0	0	0
L Income Tax	0.0	–1.1	0.0	0.0	–1.2	0.0	0.0	0.0	–1.3	0.0	–54.7	0.0	0.0	–1.5	0.0	0.0	0.0
M Net Cash Flow	0.0	2.2	0.0	0.0	2.4	0.0	0.0	0.0	2.6	0.0	106.2	0.0	0.0	2.8	0.0	0.0	0.0
N Net cash flow Alternate																	
O Net incremental cash Flow	0.0	2.2	0.0	0.0	2.4	0.0	0.0	0.0	2.6	0.0	106.2	0.0	0.0	2.8	0.0	0.0	0.0
IRR or DCF																	
NPV																	
Cum. cash flow profile	149.9	152.1	152.1	152.1	154.5	154.5	154.5	154.5	157.1	157.1	263.2	263.2	263.2	266.0	266.0	266.0	266.0



(b)

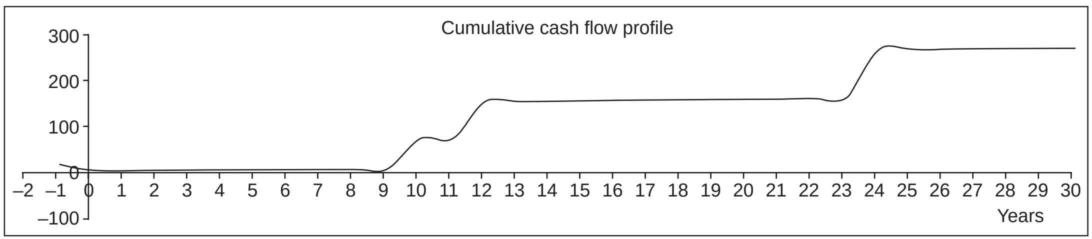
A.1 Cont'd

Example 1 — Example CUI Economics, TSA v Organic coating — Typical recoating cycle with interim inspection – with cost of CUI incident. Typical example of building up the revenue impacts (profit/expenses) to input to the cash flow analysis

	Inflation rate	2%												
	TSA coating				–120									
	CUI failure costs													
	Organic coating, repaint 12 yearly with interim inspection				–100	0	0	–2.5	0	–2.76	0	0	0	0
	Net				–20	0	0	2.5	0	2.76	0	0	0	0
	Currency units	kEuro				Revenue Start-up								
		Total	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
	Ref CNM-070-004		–2	–1	0	1	2	3	4	5	6	7	8	9
A	Investment Capital		0	0	0	0								
B	Associated Facilities	0			0									
C	Future Capital Investment	0												
D	Capital Equivalent of Lease	0												
E	Working capital	0												
F	Investment credits	0												
G	Other	0												
H	Total		0	0	0	0	0	0	0	0	0	0	0	0
I	Residual Value													
J	Gross Profit before NRE, D, T				–20	0	0	2.5	0	2.76	0	0	0	0
K	Non-Recurring Expense	0			0									
	Depreciation profile	15yr str line				0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067
	Depreciation	0				0	0	0	0	0	0	0	0	0
	Taxable income		0	0	–20	0	0	2.5	0	2.76	0	0	0	0
L	Income Tax	34%	0.0	0.0	6.8	0.0	0.0	–0.9	0.0	–0.9	0.0	0.0	0.0	0.0
M	Net Cash Flow		0.0	0.0	–13.2	0.0	0.0	1.7	0.0	1.8	0.0	0.0	0.0	0.0
N	Net cash flow Alternate													
O	Net incremental cash Flow		0.0	0.0	–13.2	0.0	0.0	1.7	0.0	1.8	0.0	0.0	0.0	0.0
	IRR or DCF	**26.3%**												
	NPV	12.0%			**32**	kEuro								
	Cum. cash flow profile		0.0	0.0	–13.2	–13.2	–13.2	–11.6	–11.6	–9.7	–9.7	–9.7	–9.7	–9.7

	Inflation rate												
	TSA coating												
	CUI failure costs	–100											
	Organic coating, repaint 12 yearly with interim inspection	0	0	–121.9	0	0	–3.365	0	0	–3.571	0	0	0
	Net	100	0	121.9	0	0	3.365	0	0	3.571	0	0	0
	Currency units												
		2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
	Ref CNM-070-004	10	11	12	13	14	15	16	17	18	19	20	21
A	Investment Capital												
B	Associated Facilities												
C	Future Capital Investment												
D	Capital Equivalent of Lease												
E	Working capital												
F	Investment credits												
G	Other												
H	Total	0	0	0	0	0	0	0	0	0	0	0	0
I	Residual Value												
J	Gross Profit before NRE, D, T	100	0	121.9	0	0	3.365	0	0	3.571	0	0	0
K	Non-Recurring Expense												
	Depreciation profile	0.067	0.067	0.067	0.067	0.067	0.067						
	Depreciation	0	0	0	0	0	0	0	0	0	0	0	0
	Taxable income	100	0	121.9	0	0	3.365	0	0	3.571	0	0	0
L	Income Tax	–34.0	0.0	–41.4	0.0	0.0	–1.1	0.0	0.0	–1.2	0.0	0.0	0.0
M	Net Cash Flow	66.0	0.0	80.5	0.0	0.0	2.2	0.0	0.0	2.4	0.0	0.0	0.0
N	Net cash flow Alternate												
O	Net incremental cash Flow	66.0	0.0	80.5	0.0	0.0	2.2	0.0	0.0	2.4	0.0	0.0	0.0
	IRR or DCF												
	NPV												
	Cum. cash flow profile	56.3	56.3	136.7	136.7	136.7	138.9	138.9	138.9	141.3	141.3	141.3	141.3

	Inflation rate									
	TSA coating									
	CUI failure costs									
	Organic coating, repaint 12 yearly with interim inspection	–3.865	0	–160.8	0	0	–4.267	0	0	0
	Net	3.865	0	160.8	0	0	4.267	0	0	0
	Currency units									
		2026	2027	2028	2029	2030	2031	2032	2033	2034
	Ref CNM-070-004	22	23	24	25	26	27	28	29	30
A	Investment Capital									
B	Associated Facilities									
C	Future Capital Investment									
D	Capital Equivalent of Lease									
E	Working capital									
F	Investment credits									
G	Other									
H	Total	0	0	0	0	0	0	0	0	0
I	Residual Value									
J	Gross Profit before NRE, D, T	3.865	0	160.8	0	0	4.267	0	0	0
K	Non-Recurring Expense									
	Depreciation profile									
	Depreciation	0	0	0	0	0	0	0	0	0
	Taxable income	3.865	0	160.8	0	0	4.267	0	0	0
L	Income Tax	–1.3	0.0	–54.7	0.0	0.0	–1.5	0.0	0.0	0.0
M	Net Cash Flow	2.6	0.0	106.2	0.0	0.0	2.8	0.0	0.0	0.0
N	Net cash flow Alternate									
O	Net incremental cash Flow	2.6	0.0	106.2	0.0	0.0	2.8	0.0	0.0	0.0
	IRR or DCF									
	NPV									
	Cum. cash flow profile	143.9	143.9	250.0	250.0	250.0	252.8	252.8	252.8	252.8



(c)

A.1 Cont'd

conventional coating using advanced NDE and NDT after recoating after 12 years (DCF of 26.0% over 30 years) and Fig. A.1(c) shows the analysis for a project using an incremental cost of €10^5 for TSA compared with a conventional coating with a CUI incident and recoating costs (DCF of 26.3% over 30 years).

Where projected life expectancy or requirement is less than 25–30 years, the cost savings from the use of TSA may not be realised and other coating options may prove optimal from a maintenance budget viewpoint.

Appendix B

Quality assurance

- The insulation contractor should submit for approval a quality plan incorporating detailed quality control and testing procedures covering all aspects of the shop fabrication and field installation of insulation systems. The quality plan and quality control procedures should comply with the requirements of ISO 9001, ISO 9002 or ISO 9003 as appropriate. The insulation contractor may propose incorporation of their own quality control procedures within the quality plan subject to review and ratification by the equipment owner.
- The procedures should as a minimum be based on the quality control agreed by both the equipment owner and the insulation contractor and should incorporate inspection verification sheets covering all work stages.
- *Hot insulation*. Specific checks that should be undertaken are as follows.
  - Surfaces certified clean and dry and any specified paint system intact, when released for insulation.
  - Application details for the following.
    - First insulation layer.
    - Second and subsequent layers of insulation (if required).
    - Weather protection sheeting.
    - Weather protection including flashings and seals.
  - Additional requirements covering the following.
    - Irregular surfaces such as flanges, valves, manways, etc.
    - Stainless steel surfaces.
    - Hot or acoustic insulation.
    - Preinsulation at a dressing yard or at a fabrication shop (where applicable).
- *Cold insulation*. Specific checks that should be be undertaken for are:
  - Inspection of metal surfaces is completed prior to insulation, supports, etc., fitted, and hydrotest completed.
  - Application details for the following.

        - First insulation layer, no gaps in joints, cracked or damaged blocks, sealer is fitted, layers are secured to specification.
        - Same as above for second layer if fitted.
        - Same as above for third layer if fitted.
        - Vapour barrier.
        - Vapour stops.
        - Flange insulation construction.
        - Valve box construction.
    - Inspection of cladding for sealing, water shed and support; rejected if sealant not under overlap.
- Insulation installation should be subject to various checks at each stage of the insulation programme.
- A pro forma should be used to steward and record each stage of the inspection; the lack of the inspection signature should not allow the next stage of the insulation to proceed.
- Owing to various different plant conditions the insulation sections should be broken down into small manageable sections: isometrics and spool pieces or vessel, shell, head, nozzles, etc.

Appendix C

Additional guidelines on the implementation of corrosion-under-insulation best practice

C.1 Maintenance and remediation issues

C.1.1 Roles and responsibilities of maintenance and operations

C.1.1.1 Maintenance

The primary roles and responsibility of maintenance with respect to the prevention of CUI are as follows.

- Whilst repairing insulated equipment, maintenance should ensure that no damage to insulation, insulation seals or other devices aimed at preventing water ingress occurs.
- If damage does occur, maintenance should carry out repairs to restore the installation to its original condition as quickly as possible.
- When working on insulated equipment, the restoration of the insulation system must be considered an integral part of the job.
- Maintenance should ensure that all work is completed in a timely fashion.
- Whilst carrying out repairs, any other areas of insulation showing distress should be included in the maintenance programme.

C.1.1.2 Operations

The primary roles and responsibility of operations with respect to the prevention of CUI are as follows.

- Whilst operating equipment, i.e. operating valves, clearing lines, steaming out systems, washing down spills, walking lines, etc., measures should be taken to avoid insulation system damage.
- If damage does occur, repairs should be initiated to restore the installation to its original condition as quickly as possible.

- It should be ensured that work orders to repair insulation damage in CUI subject areas are addressed appropriately.

C.1.2 Safety considerations

Whilst carrying out maintenance repair work on live equipment, extra safety considerations should be considered. All activities on live equipment should be risk assessed prior to implementation. There are reported instances of failures occurring on the removal of loose scale during initial inspection and even of failures on removal of insulation. It may be necessary to utilise pre-screening NDE and NDT to establish that it is safe to remove insulation, scale, etc., and for the surface preparation required for coating. Although grit blasting on live equipment is a high-risk procedure, it can be carried out after appropriate task risk assessments have been carried out.

C.1.3 Safety, health and environment concerns with asbestos and lead paint removal

Regulations are in force to prevent exposure of employees to asbestos and lead. If this is not reasonably practicable, the law says that their exposure should be controlled to the lowest possible level. Before any work with asbestos or lead paint is carried out, the regulations require employers to make an assessment of the likely exposure of employees to asbestos and lead dust. The assessment should include a description of the precautions to be taken to control dust release and to protect workers and others who may be affected by that work. Companies employing a contractor to work on their premises should make sure that either the work will not lead to asbestos or lead exposures or that the contractor has carried out this assessment and identified work practices to reduce exposures.

C.2 Minimum standards

There is a need to identify the criteria for a minimum standard.

- NACE RP0198-2004 *The Control of Corrosion under Thermal Insulation and Fireproofing Materials—A Systems Approach*

C.3 Types of insulation service

C.3.1 Equipment in cyclic service

Equipment normally operated outside the CUI temperature range but in cyclic service other than start-up and shutdown should also be included in the CUI programme. The corrosion rate during cyclic heat-up will be an order of magnitude higher than under non-cyclic conditions. Therefore it is not recommended to take any credit for the period that the equipment is operating outside the CUI temperature range, unless the cyclic frequency is very low, e.g. once every 3–4 months or less.

C.3.2 Equipment in sweating service

Equipment in sweating conditions requires site-specific considerations. Vapour barriers cannot be guaranteed to prevent the air from entering the insulation. Therefore it should be assumed that insulation on equipment that operates regularly or permanently below ambient temperature is 'wet' unless proven differently. Sweating conditions may also exist locally, e.g. in piping downstream of let-down valves, where the expansion and evaporation of the product leads to a cool-down of the product. If the initial operating temperature is sufficiently close to ambient, this cool-down can result in cold spots below ambient, resulting in water condensation under ever perfect insulation.

C.3.3 Equipment adjacent to cooling towers

Equipment which is situated close to cooling towers, especially if austenitic stainless steels are being used as materials of construction, requires specific consideration. The cooling tower drift from the exhaust plume will typically be laden with a high concentration of chlorides which can be deposited on to the equipment under certain weather conditions. Vapour barriers cannot be guaranteed to prevent the air from entering the insulation, condensing and depositing chloride residues. Both carbon–manganese steel and low-alloy steel and austenitic stainless steel piping and equipment require the use of high-integrity coatings. TSA is recommended for carbon–manganese steels and low-alloy steels to prevent CUI and aluminium foil wrap for austenitic stainless steel to prevent Cl-ESCC.

C.3.4 Equipment close to freezing point

A special case is carbon steel and low-alloy steel equipment operating just below freezing point (i.e. liquid propane at atmospheric pressure). With the insulation in good condition, it can be assumed that any water in contact with the surface will be frozen and so CUI is unlikely. This assumption is not true for the vapour phase.

C.3.5 Deluge systems

Deluge systems are not typical for insulated equipment. Nevertheless it can happen that only some parts, an instrument or a small-bore piping tie-in, are insulated. It is also possible that the deluge system was not properly designed and installed and can spray its water over adjacent insulated equipment. It is important to pay attention during visual inspection to the presence of any deluge system on or near the insulated equipment.

C.3.6 Steam tracing

Steam tracing leaks will cause greatly accelerated CUI rates and therefore steam tracing is not recommended. It is important to keep the steam tracing in good condition and not leaking. A leaking steam-tracing system is clearly a location for increased CUI rates and should therefore be part of a routine inspection procedure. Use of copper tubing will reduce the probability of steam tracing leaking; however, in the case of wet insulation, copper or any other corrosion-resistant alloy may increase the CUI corrosion rate (galvanic effect) at the higher operating temperature.

C.4 Surface preparation

C.4.1 Overview

Coating systems suitable for long-term protection against CUI must be resistant to hot-water immersion. The environment beneath insulation can be very severe. As with new construction, surface preparation and steel cleanliness are crucial in maximising the performance life of any coating system. No suitable alternatives to abrasive blasting have been found to compare favourably as it relates to performance life and/or economics. In spite of this, there is a general reluctance to perform the necessary 'grit' blasting in *in-situ* maintenance situations such as CUI.

C.4.2 Scaffolding

Scaffolding is expensive, but access for inspection, surface preparation and coating application is required. The most efficient way to minimise scaffolding is to eliminate its need through intelligent selection of inspection areas. When the inspection strategy calls for sampling of certain types of location or configuration, select those that are close to grade, near platforms, ladders or walkways. When this cannot be done, inspectors should select those that are accessible by rolling ladder or other means. For the remaining points, rope access may prove to be the most cost effective, quickest and safest alternative to traditional scaffolding or mobile crane access.

Table C.1 Surface preparation standards

Manual derusting	St 3 (in accordance with ISO 8501–2:1994)
Power tool cleaning	St2 3 (in accordance with ISO 8501–2:1994)
Wet blasting	Sa $2\frac{1}{2}$ (in accordance with ISO 8501–2:1994)
Hydro jetting	Sa $2\frac{1}{2}$ (in accordance with ISO 8501–2:1994)
Dry blasting	Sa $2\frac{1}{2}$ (in accordance with ISO 8501–2:1994)

C.4.3 Surface preparation

Depending on the surface condition, accessibility and local circumstances the following surface preparation methods are available (Table C.1).

- ISO St 2—*Deep Manual or Mechanical Cleaning*. The surface must be free of oil, grease and dirt to the naked eye and without badly adhered calamines or dust or remains of paint or extraneous materials.
- ISO St 3—*Very Deep Manual or Mechanical Cleaning*. The same as for St 2, but the surface is treated much more deeply to obtain the metallic shine which is characteristic of metal underlayer.
- ISO Sa—*Blasting*. Before blasting, any thick layers of rust must be removed with scrapers. Oil, grease and visible dirt must also be removed.
- ISO Sa 1—*Light Blasting*. The surface must be free of oil, grease and dirt to the naked eye and without badly adhered calamines or dust or remains of paint or extraneous materials.
- ISO Sa 2—*Deep Blasting*. The surface must be free of oil, grease and dirt to the naked eye and without most calamines or dust or remains of paint or extraneous materials. Any residual contamination must be firmly adhered.
- ISO Sa $2\frac{1}{2}$—*Very Deep Blasting*. The surface must be free of oil, grease and dirt to the naked eye and without calamines or dust or remains of paint or extraneous materials. The only traces of contamination admissible are insignificant stains in spots or on sides.
- ISO Sa 3—*Blasting: Until the Steel is Visibly Clean*. The surface must be free of oil, grease and dirt to the naked eye and without calamines or dust or remains of paint or extraneous materials. It must have a uniform metal colour.

C.4.4 Grit blasting

Most abrasive blast media can be classified into one of four general types (Table C.2 and Table C.3).

Table C.2 Summary of abrasive characteristics (sources [1, 2])

Abrasive	Composition	Moh hardness	Density (g/cm^3)	Dusting	Recycling
Silica sand					
Best quality	Crystalline silica	7.0	1.6	Low	No
Average quality	Crystalline silica	6.5	1.6	High	No
Staurolite or Zircon	Iron aluminium silicate	7.5	2.0	Moderate	No
Garnet					
Almandite	Iron aluminium silicate	7.5	2.0	Low	Yes
Andradite	Calcium silicate	6.5	1.8	High	No
Olivine	Iron silicate	6.5	1.9	High	No
Spec. haematite	Iron oxide	6.0	2.3	Moderate	Yes
Copper slag	Iron silicate glass	6.0	1.6	Moderate	No
Nickel slag	Nickel iron glass	6.0	1.6	High	No
Iron slag	Iron silicate glass	6.0	1.6	High	No
Coal boiler slag	Calcium, iron silicate glass	6.0	1.4	High	No
Steel grit or shot	Iron (steel)	6.0	2.2+	Low	Yes
Baking soda	Sodium carbonates	2–3	1.1	High or low*	No
Crushed glass	Alkaline silicate glass	6.0	1.6	High	No
Organic media	Various	2–3	0.6–1.0	Not applicable	No

* High dusting when used dry; low dusting when used with water.

Table C.3 Physical properties and comparative characteristics of nonmetallic abrasives (sources: [2, 3])

Description	Glass beads*	Coarse mineral abrasives†	Fine angular mineral abrasives‡	Organic soft grit abrasives§	Plastic abrasives‖
Physical properties					
Shape	Spherical	Granular	Angular	Irregular	Cylindrical (diameter-to-length ratio, 1)
Colour	Clear	Tan	Brown–white	Brown–tan	Nylon; white; polycarbonate, orange
Specific gravity	2.45–2.50	2.4–2.7	2.4–4.0	1.3–1.4	Nylon; 1.15–1.17, polycarbonate, 1.2–1.65
Free silica content	None	100%	<1%	None	None
Free iron content	<1%	<1%	<1%	None	None
Moh hardness	5.5	7.5	9.0	1.0	R-110 to R120
Media comparisons					
Toxicity	None	High	Low	Low–none	None
Metal removal	Low–none	High	High	None	Deburring only
Cleaning speed	Medium–high	High	High	Low	Low
Peening ability	High	None	None	None	None
Finish achieved	Range (various matt)	Rough anchor	Various matt	Smooth	Smooth
Surface contamination	None	Medium	Medium	Medium–high	Low–none
Suitability for wet blasting	High	Low	Low	Low	Low
Suitability for dry blasting	High	High	High	High	High
Standard size ranges	20–325 US mesh	8–200 US mesh	80–235 US mesh	60–325 US mesh	0.76 mm × 0.76 mm (0.030 in × 0.030 in) 1.1 mm × 1.1 mm (0.045 in × 0.045 in) 1.5 mm × 1.5 mm (0.060 in × 0.060 in)
Consumption rate	Low	High	Medium	High	Very low
Cost comparison	Medium	Low	High–medium	High–medium	High–medium

* Glass beads are used for cleaning, finishing, light–medium peening and deburring.
† Coarse mineral abrasives such as sand are used where metal removal and surface contamination are not considered.
‡ Fine angular mineral abrasives such as aluminium oxide are used in cleaning when smooth finish and surface contamination are not important.
§ Organic soft grit abrasives, e.g. walnut shells, are used in light deburring and cleaning of fragile items.
‖ Plastic abrasives such as nylon and polycarbonate are used to deflash thermoset plastic parts and to deburr finished machine parts.

- Natural minerals (e.g. silica sand, garnet and olivine).
- Manufactured media (e.g. steel shot, glass grit, alumina, plastic pellets or beads, solid carbon dioxide and sodium bicarbonate).
- Mineral slag (e.g. copper slag, nickel slag, iron slag and coal slag).
- Organic media (e.g. corn cobs, nut shells and starch grains).

C.4.5 Wet abrasion (jet cleaning)

This consists of water washing at a very high pressure.

- Pressure, more than 2000 barg.
- Cleaning speed, maximum 10–12 m/h, depending on the material to be eliminated.
- Use, complete elimination of coatings and rust. The result is comparable with that of dry abrasive blasting but with premature oxidisation after drying.

C.4.6 Water washing at a pressure

- Pressure, up to 1300 barg.
- Cleaning speed, maximum 5 m/h, depending on the material to be eliminated. This method, at much lower pressure, is used to eliminate contamination from any layer underneath.
- Use, elimination of salts and other contaminants, coatings and rust.

C.4.7 Wet abrasive blasting at a low pressure

- Pressure, 6–8 bar.
- Cleaning speed, maximum 10–16 m/h, depending on the material to be eliminated.
- Use, reduction in abrasion, dust, eliminates salts, avoids danger of sparking. The result is comparable with that of dry abrasive blasting but with premature oxidation after drying.

C.4.8 Steam cleaning

- Pressure, 100–120 bar.
- Use, elimination of soluble contamination is water or water emulsions; the layer under dries more quickly than on scouring with water.

C.4.9 Vacuum blasting

Vacuum blasting quickly removes surface coatings, leaving an abraded substrate, while generating minimal waste and virtually no dust emissions.

The technology offers a safe, economical and efficient means for cleaning up hazardous materials from many different types of surface. Benefits include the following.

- Increased productivity for clean-up of contaminated facilities by more than 50% over baseline.
- Minimal waste generation (1% of conventional open blasting) and virtually no dust emissions.
- Minimised worker exposure to hazardous contaminants.
- Improved ergonomics from lightweight construction of the blast head.

Although the productivity of vacuum blasting is lower than for conventional blasting which increase the cost, the total cost of vacuum blasting may be similar because of lower scaffolding and sheeting requirements.

C.4.10 Mechanical surface preparation

The cost associated with dust containment and debris disposal may be significant but the improvement in coating integrity and therefore life means that blasting should always be applied wherever possible. When blasting cannot be successfully applied, it will be necessary to use power tools or manual preparation techniques. It should be recognised that in these cases the coating life will be substantially shortened and reinspection schedules should be set accordingly. These methods are not recommended but sometimes are unavoidable.

C.4.10.1 Mechanical brushing

Mechanical brushing is usually performed with rotating wire brushes. The main disadvantage is that the surfaces treated are not usually corrosion free and are often polished and contaminated with oil. This makes the adhesion of any coating less effective and impairs the system's performance.

C.4.10.2 Descaling

Mechanical descaling is usually carried out in combination with mechanical brushing. It is appropriate for small repairs and can be used to eliminate thick coats of rust and to make subsequent blasting operations cheaper.

C.4.10.3 Pin hammer

This is utilised to eliminate rust, paint, etc., from corners and angles and obtain a clean surface with a profile.

C.4.10.4 Sanding with grinding discs

Sanding with a grinding disc requires the use of one or more rotating discs covered with an abrasive material. The system is used for small repairs or for eliminating particles and notches.

C.4.11 Non-dust (vacuum) grit blast technology

Alternative grit blast techniques such as the following should be considered in order to reduce dust contamination. Dust control is simplified (no boxing in structures) and the risk of personal eye injuries is reduced.

C.4.11.1 Sponge jet

Sponge jet is a composite of urethane sponge and a cleaning (or abrasive) agent; this patented technology utilises the pliable open-celled characteristics of urethane sponge and the cleaning and cutting power of a cleaning agent or conventional abrasive. The pliant nature of sponge medium allows it to flatten on impact, exposing the cleaning agent or abrasive. After leaving the surface, then it constricts (entrapping most of what would normally have become air-borne contaminants). Blasted medium is collected and processed through either electric or pneumatic classifiers, which separate the sponge medium abrasives into three categories: oversized debris, reusable medium and fines (consisting of spent media and dust). Up to 94% of sponge medium abrasives are reusable after each blast cycle.

C.4.11.2 Solid carbon dioxide

There are four cleaning methods using carbon dioxide.

- Macroscopic hard and dense dry ice pellets.
- Softer microscopic ‘snow’ particles.
- Liquid carbon dioxide washing systems.
- Supercritical fluid carbon dioxide.

Whichever process is used, cleaning depends on the liquid carbon dioxide solvent properties, the energy and momentum transfer by the impacting solid phase, or a combination of solvent properties and momentum or energy transfer. Pellet systems rely upon the thermomechanical impact stresses related to the high impact velocity of macroscopic pellets for contamination removal—a momentum and energy transfer process. Snow sprays rely upon a combination of the solvent action of liquid carbon dioxide and the momentum transfer of high-velocity microscopic snow particles. The liquid-based carbon dioxide washing systems rely on the liquid-phase solvent properties. Finally, the supercritical fluid carbon dioxide systems rely exclusively upon carbon dioxide's unique supercritical fluid properties.

C.5 References

1. J.D. Itansink, 'An introduction to abrasives for protective coating removal operations', *J. Prot. Coatings Linings*, 2000, **17**(4), 66–73.
2. PERA, Research Report, 2003.
3. 'Pickling of iron and steel', in *ASM Metals Handbook*, Vol. 5, 9th edition, Metals Park, Ohio, American Society for Metals, 1982, Table 4, p. 85.

Appendix D
Coatings

D.1 General comments

Protective coatings include thermally sprayed or flame-sprayed metallic systems as well as the traditional organic coating systems. Each of these systems has its place in the prevention of CUI. Some are more effective then others but may cost more. An economic life cycle analysis can be very effective in determining which system to apply in a particular situation. This document will not include a detailed discussion of the various types of coating that are available, which can be used to protect piping and vessels that will be insulated. The reader is encouraged to consult NACE RP0198-2004 [1] for guidance as it contains a very detailed section on protective coatings.

D.2 Protective coatings

This section details information for the selection of protective coatings for carbon–manganese steels, low-alloy steels and austenitic stainless steels under thermal and/or noise reduction insulation systems and cementitious fireproofing. Protective coatings have been recognised and accepted and are recommended as a highly effective method of protecting insulated metallic substrates such as these steels from corrosion. Attempts to prevent water from entering insulated systems have not been successful, and corrosion protection techniques such as inhibitors and cathodic protection have been less effective than protective coatings in mitigating CUI.

D.3 Thermally sprayed aluminium

A comparison between TSA and conventional paint systems for the protection of steel under insulation is provided in Table D.1.

Table D.1 Comparison between TSA and conventional paint systems

Feature	TSA	Conventional paint
Protection in CUI temperature range	25+ years	5–13 years, depending on environment (sweating or dry)
Protection in cyclic service	Yes	No
Upper continuous operating temperature	480 °C	175 °C
Chemical resistance	Resistant to solvents and pH 4–9	Not resistant to solvents; wider pH range
Cure time between coatings	None (one coat only)	Approximately 24 h (multiple coats required)
Environmental impact	None for aluminium coating	Must meet volatile organic compounds and disposal regulations
Durability	Very resistant to mechanical abuse Minor damage *will not* result in corrosion	Very susceptible to mechanical abuse Any damage to coating *will* result in corrosion
Required surface preparation	Sa $2\frac{1}{2}$ (near white)	Sa $2\frac{1}{2}$ (near white)
Application method(s)	Spray only	Spray, brush and roller
Application accessibility	Must have sufficient access to bring applicator head within 30° normal to surface	Able to apply to surfaces with restricted access using brushes and rollers
Temperature limit for application	None but surface must be dry	Ambient to 60 °C
Work permit required	Hot work	Cold work but hot work can be restricted in the area

D.4 Surface and moisture tolerance

When the above situations cannot be avoided, the use of a surface- and/or moisture-tolerant coating may be considered as a short-term measure. It is recommended that a specialist with expertise in coatings select these coatings.

D.5 Alternative coatings; tape coatings

In some situations where grit blasting is not acceptable, liquid applied coatings are not necessarily the best answer. Wax or petrolatum tape wrap systems are sometimes the best solution for corrosion prevention under insulation on piping where the operating temperature will not exceed 55 °C (130 °F). These coatings have a limited life.

Glass-fibre-reinforced resin in tape or sheet form can be used in lieu of a conventional organic coating or TSA, but it is a costly process and would not normally be the first choice. However, the application of tape at locations where clamps, etc., are to be used not only acts as a buffer preventing coating damage but also prevents local moisture retention between the clamp and pipe from accelerating the degradation of the coating. Inserts such as rubber also prevent the damage but not the crevice water retention.

D.6 Reference

1. NACE RP0198-2004 *The Control of Corrosion under Thermal Insulation and Fireproofing Materials—A Systems Approach*, Houston, Texas, NACE International, 2004.

Appendix E
Application of thermally sprayed aluminium

E.1 Application of thermally sprayed coatings

Thermally sprayed coatings are applied by a process in which a metal powder, an organic powder or metal wire is melted and spray deposited on to a surface. Historically, metallising was the term used to describe wire flame spraying. However, owing to dramatic improvements in the equipment used to heat and spray the molten metal and non-metallic polymers on to a surface, the term thermal spraying is more descriptive. Thermal spraying is a process by which a finely divided molten metallic or non-metallic material is sprayed on to a prepared substrate to form a coating. The sprayed material is originally in the form of a wire or powder; wire is the preferred feedstock for TSA. The thermal spray gun heats the wire to a molten state, and compressed gas propels it to the surface being coated and deposits it into a film.

Zinc, aluminium and their alloys are the metals most widely used for thermally sprayed, corrosion-resistant coatings. These metals provide excellent corrosion protection in a variety of marine and industrial environments. In general, aluminium corrodes less rapidly than zinc in highly acidic conditions, but zinc performs better in alkaline environments. Aluminium is the preferred material owing to possible SHE concerns (related to dust production during thermal spraying) with the use of zinc alloys in confined environments. After spray application, the coatings are anodic to the underlying steel surface. When corroded, the oxidised aluminium coating functions primarily as a barrier coating.

One advantage of the thermal spray system is that essentially no start-up or clean-up procedures are involved. The wire feedstock is fed to the spray gun, the heat source is ignited, and spraying of the molten feedstock begins. On conclusion of thermal spraying, the device is shut off, and the process stops, with virtually no equipment clean-up required.

The particles bond to the substrate mechanically. The particle velocity, substrate roughness, particle size, material chemistry, particle temperature and substrate temperature influence the bond strength of the coating material. The process was originally referred to as flame spraying, metal spraying, flame plating or metallising, when it was limited to the oxygen-fuel (oxy-fuel) wire spraying method.

Wire flame-sprayed coatings generally exhibit lower bond strengths, higher porosity, a narrow working temperature range and a higher heat transmittance to the substrate than plasma or electric-arc-sprayed coatings.

Currently five major commercially available thermal spraying processes are in use. We are typically only interested in the first two.

- Oxy-fuel wire spraying.
- Twin-wire electric arc spraying.
- Oxy-fuel powder spraying.
- Plasma arc powder spraying.
- High-velocity oxy-fuel powder spraying.

E.1.1 Oxy-fuel wire spraying (flame spraying)

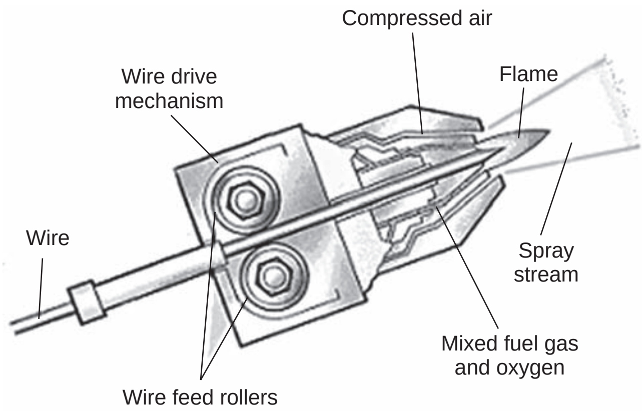
The oxy-fuel wire spray process (also called wire flame spraying or the combustion wire process) is the oldest method for obtaining thermally sprayed coatings and requires among the cheapest capital investment. Acetylene or other common fuel gases are combined with oxygen and ignited in the spray gun. The coating material is usually in wire form although solid rod feedstock has also been used. During operation, the wire is drawn into the flame by drive rollers that are powered by an adjustable air turbine or electric motor. The tip of the wire is melted as it enters the flame and is atomised into particles by a surrounding jet of compressed air and propelled to the workpiece (Fig. E.1).

Wire flame-sprayed coatings generally exhibit lower bond strengths, higher porosity, a narrower working temperature range and a higher heat transmittance to the substrate than plasma- or electric-arc-sprayed coatings.

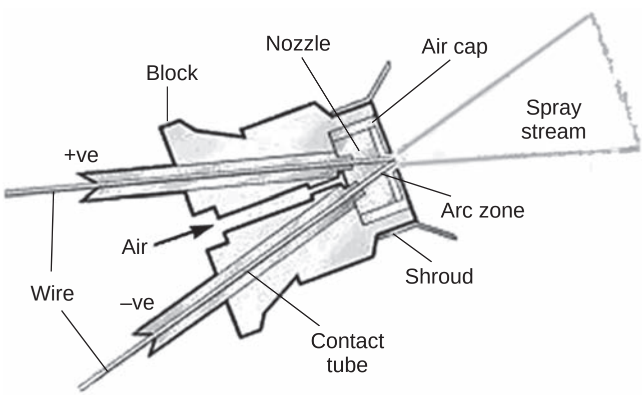
E.1.2 Twin-wire electric arc spraying

Electric arc wire spraying also applies coatings of selected metals in wire form. Push–pull motors feed two electrically charged wires through the arc gun to contact tips at the gun head. An arc is created that melts the wires at temperatures above 5500 °C. Compressed air atomises the molten metal and projects it on to a prepared surface (Fig. E.2).

Because of the high temperatures in the arc zone, the coatings have excellent adhesion and high cohesive strength. Superheating of the particles after impact may lead to a metallurgical ‘weld’ bond with some metals, substantially increasing adhesion and cohesive strength.



E.1 Schematic diagram of the flame spray nozzle.



E.2 Schematic diagram of the twin-arc electric nozzle.

E.2 Use of organic topcoats

Organic sealers or topcoats are commonly used over the thermally sprayed metal to extend the life of the system. Common sealers include many of the synthetic resin coating systems, especially vinyls, epoxies, polyurethanes and phenolics. Sealers are essential for most immersion or severe chemical corrosion applications. Most sealers are applied in at least two coats, the first of which is thinned for penetration into the pores of the thermally deposited metal coating. The second and sometimes third coats of a sealer are applied undiluted as build coats.

Because there are no solvents or volatile material in any metallic thermal spray system, volatile organic compound compliance is not a problem. However, it may be an issue if an organic sealer coating is used.

E.3 Application strategies

TSA can be applied to all equipment fabricated from carbon–manganese steels and low-alloy steels and if required to both austenitic and duplex stainless steels. The application is more economic when applied to new equipment in dedicated fabrication shops but TSA can also be applied in the field in maintenance or project facilities and directly on to piping and equipment *in situ*. TSA is therefore applicable for similar applications as paint and conventional coatings.

- Off-site, on all new fabrications (vessels, tanks, piping, etc.).
- Off-site, or in the field on all new fabrications.
- Off-site, in maintenance areas (equipment removed from service).
- On-site, during maintenance turn-arounds (equipment taken out of service).
- On-site, on equipment taken out of service whilst other plant is running.
- On-site, on live equipment.

Procedures and application specifications need to be developed for TSA application in the field, especially when application on live equipment containing flammable hydrocarbons is considered. Generally, coatings obtained by oxy-fuel wire spraying are preferred over these obtained by twin-wire electric arc spraying for site TSA application on piping and vessels with limited access. This is based on experience which shows that the former coatings are easier to apply and have fewer SHE-related issues. The bond strength of TSA obtained by oxy-fuel wire spraying is generally lower than the bond strength of TSA coatings obtained by twin-wire electric arc spraying but is nonetheless considered more than acceptable from a fitness-for-purpose perspective. This is also true for live equipment applications because of the less stringent permit procedures that are required. Twin-wire electric arc spraying permits a higher application rate than oxy-fuel wire spraying in less congested areas such as large tanks and other large equipment which can be used to lower the overall cost of application. Selection of the TSA application process for shop-applied applications should be made following an economic assessment.

Table E.1 shows some of the advantages of using TSA over conventional organic coatings when considering application on live equipment.

E.4 Thermally sprayed aluminium specification

This specification outlines the requirements for the protection of externally insulated vessels and piping surfaces from CUI by the application of TSA.

Table E.1 CUI prevention on-line field application: TSA and paint

Features	TSA	Conventional paint
CUI protection	25–30 years; maintenance free; inspection free	5–13 years; tends to low side for on-line application
Protection in cyclic service	Yes	No effective paint system
Upper continuous operating temperature	480 °C (If a seal coat is not applied) Limiting temperature for sealed coatings will depend on the sealer used	175 °C (upper temperature of 540 °C for specialist coatings)
Schedule impact	None; one-coat application (if a seal coat is applied, then same cure required as for paint)	24 h typically; multiple coats required
Environmental impact	None (for seal coat, same as paint)	Must meet volatile organic compounds and disposal regulations
In-place cost ratio	1.05–1.20	1.0
Durability	Very resistant to mechanical abuse Minor damage does not result in CUI	Very susceptible to mechanical abuse Any damage results in CUI
Required surface preparation	SA $2\frac{1}{2}$ (near white)	Sa $2\frac{1}{2}$ (near white)
Application method(s)	Twin-arc spray or flame spray (for seal coat, as for paint)	Spray, brush and roller
Application accessibility	Arc or spray head to within an angle of 30° normal to surface	Brush or roll for restricted access but life decreases
Temperature limit for application	None but surface must be dry unless applying seal coat	Ambient to about 60 °C
Work permit required	Hot work	Cold work, but it can restrict hot work in the area where painting is taking place

Table E.2 Definitions

Client or owner	The eventual equipment owner
Contractor	The actual company carrying out the work
Coating contractor	The company responsible for the defined piece of coating work, including the supply of the materials
Manufacturer	The manufacturer of the coating materials
Supplier	The supplier of the item requiring coating, which may not necessarily be the coating contractor
Shop	Preparation and coating of new bare steel surfaces in a supplier's or coating contractor's shop or plant works prior to transportation to the site of construction, or a controlled environment coating facility erected at the permanent site of construction

- The extent of TSA coating shall include all vessel and pipework surfaces including nozzles, brackets, attachments and insulation support rings. Vessel skirts and saddles should also be TSA coated when applicable and identified accordingly in contract documentation.
- This specification covers both on-site and off-site TSA application.
- Excluded from this specification are details of the safety issues involved with the TSA process. This shall be contained in other contract documentation.

E.5 Definitions

Definitions of terms used in this specification are provided in Table E.2.

E.6 Referenced codes, standards and specifications

The latest revisions, unless otherwise stated, of the standards and codes of practice listed in Table E.3 shall apply where relevant to work covered by this specification.

E.7 Coating philosophy

- The application of the TSA systems shall only be performed by approved coating contractors.
- The coating contractor operator qualifications shall be evaluated to AWS C2.18 or AWS C2.23, or to the client-agreed equivalent.
- The coating contractor shall provide an operator experience list and TSA procedures for client or contractor review and agreement prior to contract award.

Table E.3 Referenced standards and codes

ISO 8501-1	*Preparation of Steel Substrates before Application of Paint and Related Products—Visual Assessment of Surface Cleanliness*
ISO 8502-3	*Preparation of Steel Substrates before Application of Paint and Related Products—Test for the Assessment of Surface Cleanliness—Part 3 Assessment of Dust on the Steel Surfaces Prepared for Painting (Pressure-sensitive Tape Method)*
ISO 8503	*Preparation of Steel Substrates before Application of Paint and Related Products—Surface Roughness Characteristics of Blast-cleaned Substrates*
ISO 209-1	*Wrought Aluminium and Aluminium Alloys—Chemical Composition and Forms of Products—Part 1: Chemical Composition*
ISO 4624	*Paints and Varnishes—Pull-off Test for Adhesion*
AWS C2.18	*Guide for the Protection of Steel with Thermal Sprayed Coatings of Aluminum and Zinc and their Alloys and Composites*
AWS C2.23	*Specification for the Application of Thermal Spray Coatings (Metallizing) of Aluminum, Zinc, and their Alloys and Composites for the Corrosion Protection of Steel*

- Qualifications and details shall only be submitted for those operatives designated to perform the production work; additional and/or replacement operatives shall not be used without agreement from the client or contractor following review of their qualifications and experience details.
- Direct evaluation of work carried out by the applicator on comparable equipment that has operated for at least a full year should be conducted where possible.
- Subject to review of the contractor and operative documentation, the client or contractor may require practical qualification tests, as defined in AWS C2.18, Appendix C, to be carried out by the operatives designated to perform the production work.

E.8 Coating system

- Coating dry film thickness readings shall be taken by the coating contractor and/or supplier. The client and contractor shall conduct selective quality checking by taking independent dry film thickness readings.
- Readings shall be any single minimum–maximum method. The frequency of the single point readings shall be agreed with the client.
- Ordinary dry film thickness gauge can be used. Readings from the anchor pattern must be recorded before coating for later deduction from coating readings.
- The frequency and location of the thickness checks shall be proposed by the coating contractor and included in the submitted quality plan.

Table E.4 TSA surface preparation

Surface preparation	Coating system	Thickness range
Cleanliness, ISO 8501 Sa $2\frac{1}{2}$ Roughness, ISO 8503 Grade medium G (75 µm minimum)	Thermally sprayed aluminium with or without seal coat	200–250 µm (excluding sealer)

- The blast anchor pattern readings shall be taken by the coating contractor in accordance with the client or contractor-agreed quality plan.
- The acceptable pull-off adhesion test value is 6.9 MPa (1000 1bf/in^2) minimum for new test plate.

E.9 Thermally sprayed aluminium material

Surface preparation of TSA is as given in Table E.4.

- The material for metal spraying shall be commercially pure aluminium with an aluminium quality at least equal to Al 99.5 of ISO 209-1. Use of other alloys should be reviewed with the client prior to application.
- All metals shall be supplied with product data sheets and quality control certificates, and be marked with the metal manufacturer's name, manufacturing standard, metal composition, weight and manufacture date.

E.10 Seal coat

The addition of seal may be required and will be specified on a case-by-case basis by the client. To enable the client to make the decision the supplier and/or coating contractor shall supply the following details with his bid documentation.

- Specification, including thickness, and data sheets for proposed seal coat. (Temperature range for sealers should be as stated.)
- Time to apply the seal coat per vessel and/or piping system.
- Cost per vessel and/or piping system to apply the seal coat.
- The temperature range of proposed sealer coat material shall be as given in Table E.5.
- The sealer coat material shall be compatible with the substrate and approved by the contractor and client. Aluminium and titanium dioxide pigments aid sealer performance while alkaline materials such as sodium silicate will damage it.
- The sealer shall be applied until the absorption is complete. In the case of an epoxy sealer, one thinned coat shall be applied to obtain optimum

Table E.5 Sealer temperature ranges

Surface temperature range
–20 °C minimum to 120 °C maximum
120 °C and greater

penetration, followed by a second coat of the same material without thinning.

E.11 Design

- Welds shall not be coated until all approved heat treatment, non-destructive testing and pressure testing has been completed and approved.
- Certificates of release, confirming that successful completion of all appropriate tests and safety checks have been carried out to the released working areas, shall be obtained before the commencement of coating work.
- The following items shall be shielded and protected to prevent damage during surface preparation and coating material application operations. All openings, including those that are flanged or threaded shall be sealed to prevent entry of blast abrasive or coating material. After completion of coating operations, all material used for shielding and sealing shall be removed unless instructed otherwise.
  - The sum of yearly costs due to unavailability of system and loss of earnings.
  - Nameplates.
  - Packing glands and seals.
  - Vents.
  - Valve stems.
  - Instrument dials.
  - Gauge and flow indicator glasses.
  - Pressure gauges.
  - Machined surfaces of gasket contact surfaces.

E.12 Surface preparation

Surface preparation for TSA is as given in Table E.4.

- The coating contractor shall grit blast the vessel and/or surface to ISO 8501 Grade Sa $2\frac{1}{2}$ (near-white blast finish).

- An anchor pattern of 75 μm minimum shall be achieved using an angular grit.
- The abrasive size shall be selected to achieve a surface roughness specified to ensure the adhesion of the sprayed coating and shall be more coarse than normally used for painting.
- Abrasive blast cleaning employing sand or slag abrasive from mineral smelting is not permitted.
- The abrasive shall be clean and dry, and free from soluble salts.
- The surface shall be dust free prior to application of the thermal spray coating.
- The coating contractor shall consider how large an area to blast prior applying the TSA coating (i.e. how long the blast will hold) and shall include this in the overall coating plan.

E.13 Weather and surface conditions

Surface preparation and coating shall not be undertaken when any of the following conditions exist.

- In conditions which are favourable to surface condensation.
- When the relative humidity is above 85%.
- If there is the likelihood of a change in weather conditions within 4 h of the application which would result in air temperatures below those specified or the deposition of moisture upon the surface.
- On metal surfaces having temperatures less than 3 °C above the dew point.

E.14 Application process

- The application process may be oxy-fuel wire spraying or twin-wire electric arc spraying.
- The preferred material feed mechanism for in field application is wire feed. Powder feed mechanisms are acceptable alternatives for shop-applied work but must be approved by the client for site application.
- The spray pattern should be in a block form layer and shall overlap on each pass of the gun. The coat shall be applied in multiple layers at right angles to the previous layers (box pattern).
- The success of TSA application is greatly dependent on the application technique, the head travel speed and the distance from the surface being coated. The application technique shall be detailed in the coating contractor's application procedure and verified and monitored by the area foreman during the application process.

- The sprayed coating should be visibly free of lumps, blisters and loosely adhering particles.
- When applying TSA, production test plates shall be prepared for the purpose of adhesion testing during the TSA application process. The test plates shall provide similar geometrical complexity to the item to be coated, shall be prepared and coated concurrently with the item and shall be supplied one per shift. The plates shall be approximately 300 mm × 300 mm × 6 mm. The panel shall be blast cleaned and TSA coated in such a manner to show both processes equally split over one face of the panel. On completion of coating the panel, three adhesion tests shall be carried out to ISO 4624 and measured against the requirements of this specification.

E.15 Specific requirements for on-site thermally sprayed aluminium application

- The grit blasting and TSA coating application shall avoid damage to gaskets, cables, instruments, valves, etc., by using appropriate sheeting and/or shielding. The design of the sheeting and/or shielding shall be agreed between the coating contractor, the contractor and the client.
- The coating contractor, in general, is responsible for sheeting instruments, etc., using fire retardant sheeting. However, a site visit prior to application will reveal any areas where the client will be required to assist with protection or removal for access. The protection of these items should be inspected and approved by the client before grit blasting and thermal spraying commences.
- The coating contractor shall grit blast surfaces using an vacuum-type process when requested by the client.

E.16 Piping field welds

- The surface finish shall be as close to ISO 8501 Grade Sa $2\frac{1}{2}$ (near-white blast finish), as practical, using angular grit.
- The anchor pattern shall be as close to 75 µm as practical.
- Slag abrasive from mineral smelting shall not be used.
- Moisture shall not be present on the steel surface and spraying should not take place when the steel temperature is less than 3 °C above the dew point.
- Existing TSA coating of pipe work shall be feathered back a minimum of 100 mm before a new coating is applied. Care should be taken not to apply new TSA coatings to seal coated surfaces.

- Full quality assurance documentation is not required for this process, but coating thickness readings shall be marked on the adjacent pipe for checking.

E.17 Inspection and acceptance

Before commencement of work the coating contractor shall determine witness or hold points for examination of the following areas during the work.

- Qualification records before starting work.
- Witnessing of test plates for individual operators. This will include a surface profile after grit blasting, pull-off tests, bend tests and thickness tests.
- Surface preparation and profile before applying the metal coating.
- Metal coating before applying the seal coat.
- Seal coat after dried or cured to permit handling (if applied).
- The coating contractor shall be responsible for inspection and tests including all tools needed for quality control.
- Any areas identified as being below the requirements of this specification shall be corrected immediately. Repair and correction methods shall be client or contractor agreed.
- The client or contractor reserves the right to inspect all phases of shop and field cleaning, surface preparation and coating operations to ensure that the coating contractor is accurately following the recommendations and requirements of this project specification and the manufacturer's instructions. This inspection shall not be used as a substitute for adequate coating contractor supervision and inspection nor the coating contractor's own quality assurance and quality control systems and procedures.
- The coating contractor shall keep an accurate daily record of air temperatures and humidity conditions and the times of commencement and cessation of all phases of the cleaning, surface preparation and painting operations. These records, which shall be certified accurate by the coating contractor's painting supervisor, shall be available for inspection by the contractor at all times.
- Final acceptance will be by the client and will only be made a minimum of 24 h after the application to allow rust bloom of any low thickness areas to develop. The client may at their discretion request that the equipment is sprayed with fresh water to accelerate this process if thought necessary.
- Any areas found with rust bloom after this period and found to have a coating less than required in this specification shall be grit blasted and recoated to the satisfaction of the client.

Table E.6 Testing and inspection requirements

Test type	Method	Frequency	Acceptance criteria	Consequence
Environmental conditions	Ambient and steel temperature Relative humidity Dew point	Before start of each shift + minimum twice per shift	In accordance with specified requirements	No blasting or coating
Visual examination of substrate	Visual for sharp edges, weld spatter, slivers, rust grade	100% of all surfaces	No defects	Defects to be repaired
Cleanliness	ISO 8501–1 ISO 8502-3	100% visual of all surfaces Spot checks	ISO Sa $2\frac{1}{2}$ Maximum quantity and size rating 2	Reblasting Recleaning and retesting until acceptable
Roughness	Testex Press-O-Film, X-Coarse 37–113 µm replica tape	Once per 2 m^2	75 µm (minimum)	Reblasting
Visual examination of coating	Visual	100% of surface after each coat	Surface shall be uniform and free of lumps, loosely adherent spattered metal, bubbles, ash formation, defects and uncoated spots	Repair defects
Coating thickness	Single-point maximum and minimum	To be agreed with the contractor and the client	200–250 µm minus surface profile	Repair, additional coats or recoating as appropriate and approved by the contractor and the client
Adhesion	ISO 4624 using equipment with an automatic centred pulling force, and carried out when fully cured	Each test plate on new steel	6.9 MPa minimum	Coating to be rejected

- Failure by the client's inspector to detect a deficiency, or waiver of client inspection, does not relieve the coating contractor of responsibility for quality or performance of the coating as required by contract. The testing and inspection shall be in accordance with the requirements listed in Table E.6.

E.18 Documentation

- The coating contractor shall submit procedures with their tenders for application process, operator qualification and training, and quality for client or contractor agreement. A control plan, preferably to AWS C218 or AWS/SSPC CS 2.23, is required for review and agreement prior to contract award.
- The final coating documentation package shall include the operating parameters of equipment, application operative's name, blast profile, TSA dry film thickness measurement data, pull-off test results and application environmental condition data.

E.19 Surface and moisture tolerance

When the above situations cannot be avoided, the use of a surface- and/or moisture-tolerant coating may be considered as a short-term measure. It is recommended that a specialist with expertise in coatings select these coatings.

E.20 Alternative coatings; tape coatings

In some situations where grit blasting is not acceptable, liquid applied coatings are not necessarily the best answer. Wax or petrolatum tape wrap systems are sometimes the best solution for corrosion prevention under insulation on piping where the operating temperature will not exceed 55 °C (130 °F). These coatings have a limited life.

Glass-fibre-reinforced resin in tape or sheet form can be used in lieu of a conventional organic coating or TSA, but it is a costly process and would not normally be the first choice. However, the application of tape at locations where clamps, etc., are to be used not only acts as a buffer preventing coating damage but also prevents local moisture retention between the clamp and pipe from accelerating the degradation of the coating. Inserts such as rubber also prevent the damage but not the crevice water retention.

Appendix F
Types and forms of insulation material

The most commonly used industrial insulation materials are described below. Generic references to the thermal insulation material as rock wool, mineral wool, mineral fibre, etc., shall be interpreted in accordance with the definitions given in ASTM C547, ASTM C612, BS 3958: Part 4 and BS 3958: Part 5 (as man-made mineral fibre made from rock, slag or glass, processed from a molten state into a fibrous form with a suitable binder). For the purposes of this document, materials of a rock composition (diabase, silica ore, basalt or similar types) shall be acceptable. Materials made from slag (in part or in whole) shall not be acceptable. Fibrous materials made of glass shall only be permitted where specified as expansion joint filler.

F.1 Mineral fibre

ASTM groups commercial glass and mineral fibre materials into a single category, generally described as rocks, slag or glass processed from a molten state into a fibrous form with organic binders. Mineral fibre is generally specified for ambient to high temperatures, the upper temperature being dependent on the specific fibre and binder used.

Both the water absorption characteristics and the ability to repel water are variable and are dependent on the specific fibre and binder used. Some binders break down in the presence of heat and water, which leads to wicking.

Preformed mineral fibre insulation shall be of a rock composition complying with physical characteristics listed in BS 3958: Part 4 and BS 3958: Part 5 and, where these do not conflict, physical characteristics listed in ASTM C612 and C547. The material shall be a water-repellent grade complying with the following overriding requirements.

- *Combustibility.* Non-combustible when tested in accordance with BS 476: Part 4, ASTM E136 or ISO 1182.
- *Chemical requirements.* Less than 10 ppm chloride, and less than 10 ppm fluoride, when tested in accordance with ASTM C871, with a combined

halide content no greater than 15 ppm. All material shall be qualified for use on austenitic stainless steel in accordance with ASTM C795 by conforming to the preproduction test requirements of ASTM C692 and the confirming quality control requirements for chemical analysis of ASTM C871. These standards require 50 ppm sodium silicate for up to 20 ppm chloride.

- *Shot content.* Less than 6% by weight of shot exceeding 250 μm when tested in accordance with Section 14 of BS 2972, and less than 31% by weight of shot or coarse fibres between 63 and 250 μm.
- *Content of sulphur compounds.* Less than 0.5% by weight.
- *Alkalinity.* pH of between 7 and 8 when tested in accordance with Appendix C of BS 3958: Part 4 and BS 3958: Part 5.
- *Optimum service temperature range.* From 20 °C to 650 °C.
- *Thermal conductivity.* No greater than given in Table F.1, when tested in accordance with Section 4 of BS 2972.
- *Water retention.* When tested in accordance with an authoritative modification to Section 12 of BS 2972 approved by the engineer (covers test specimens of preformed pipe section, nominal pipe size 250 mm (25 mm thick and 25 mm deep)) as well as the flat slab sample specified in BS 2972, the maximum acceptance values in Table F.2 shall be achieved.
- *Binder.* Resin impregnation during manufacture prior to compressing and curing.

Table F.1 Thermal conductivity of mineral fibre insulation

Mean temperature (°C)	Thermal conductivity of a slab or sections of mattresses (W/m K)
50	0.037
100	0.044
150	0.052
200	0.061
300	0.082
350	0.096
400	0.111

Table F.2 Water retention in mineral fibre insulation

Partial immersion	Total immersion
0.2 kg/m^2 at 20 °C	20 kg/m^3 at 20 °C
0.2 kg/m^2 at 250 °C	20 kg/m^3 at 250 °C

- *Proportion of fine fibres.* 31% or less of fibres of diameter less than 3 μm in the bulk fibrous material.
- *Facings for flexible mattresses.* Facings shall consist of 0.9 mm × 25 mm mesh wire netting sewn with wire ties at close regular intervals in such a way as to ensure that these cannot be pulled through during storage, handling and fabrication. The wire mesh shall be stainless steel for application to stainless steel vessel heads and galvanised for other applications. The facing shall be on both sides.
- *Dimensional tolerances.* Tolerance on thickness, length and inside diameter shall conform to requirements of BS 3958: Part 4 or ASTM C547.
- *Densities and forms.* The following minimum densities and forms of preformed mineral fibre pipe sections and slabs shall be used as the first and second layers up to 500 °C, and as the second and third (outer) layers only, for temperatures above 500 °C.
    - Piping, with pipe sections of 125–155 kg/m^3 density, either in two halves or in one piece hinged (snap-on) for all sizes up to maximum commercially available pipe size. For larger diameters, factory-cut bevelled lags of 140 kg/m^3 density shall be employed.
    - Heat-traced piping, with pipe sections as for piping but oversized generally up to the next commercially available size to accommodate parent line and its accompanying tracer.
    - Equipment having a diameter up to maximum commercially available pipe size, with pipe sections as for piping.
    - Vertical equipment having a diameter exceeding maximum commercially available pipe size; bevelled lags and rigid slabs of 140 kg/m^3 density for all single, inner and outer layers.
    - Horizontal equipment having a diameter exceeding maximum commercially available pipe size: bevelled lags and rigid slabs of 120 kg/m^3 density for all single, inner and outer layers.
    - The following nominal densities of preformed mineral fibre mattresses shall be used:
        - Flexible mattresses for equipment heads of 125–138 kg/m^3 density for all operating temperatures. Note that the nominal densities of mattresses shall exclude metallic facings and shall be within a tolerance of 15% as per Section 7.2 of BS 3958: Part 3.
    - For hot face temperatures up to 650 °C, the concentration of organic bonding material for all specified insulation densities shall not constitute a fire risk through the incidence of welding sparks or through an internal self-heating phenomenon (punking) over the range of insulation thicknesses and individual layers proposed by the engineer. The manufacturer of the material shall demonstrate to the requirements of Section 18 of BS 2972 that the degree of self-heating does not exceed safe limits.

F.2 Low-density glass fibre

Low-density glass-fibre blanket (unfaced) for packing voids or for introduction at expansion–contraction joints shall be manufactured from long continuous textile-type glass fibres chopped into 50–100 mm lengths and firmly bonded in random orientation with an inert thermosetting resin. The material shall have the following minimum properties.

- *Density*. 23.0–24.0 kg/m^3.
- *Thermal conductivity*. No greater than 0.034 W/m K at 25 °C mean temperature when tested in accordance with ASTM C177.
- *Service temperature*. Up to 230 °C.

The 100% glass fibre matt for lining reusable insulation covers and for introduction at expansion joints above 230 °C shall be composed of E-glass fibres in the form of a web which is needled together without chemical binders and having a low (less than 10 ppm) chloride level. The material shall have the following minimum properties.

- *Density*. 140–150 kg/m^3.
- *Thermal conductivity*. No greater than 0.058 W/m K at 150 °C mean temperature when tested in accordance with BS 874.
- *Service temperature*. Up to 500 °C.

F.3 Calcium silicate

Calcium silicate preformed insulation shall consist of reacted hydrous calcium silicate containing well-opened asbestos-free reinforcing fibre. It is hygroscopic and readily absorbs water. The material shall comply with BS 3958: Part 2 or ASTM C533 and the following additional requirements.

- *Combustibility*. Non-combustible when tested in accordance with BS476: Part 4.
- *Chemical requirements*. All material shall be qualified for use on austenitic stainless steel in accordance with ASTM C795, by conforming to the preproduction test requirements of ASTM C692 and the confirming quality control requirements for chemical analysis of ASTM C871. These standards require 50 ppm sodium silicate content for up to 20 ppm chloride.
- *Optimum service temperature range*. From 20 °C to 730 °C.
- *Thermal conductivity*. No greater than given in Table F.3 when tested in accordance with BS 874.
- *Bulk density*. 190–240 kg/m^3.
- *Flexural strength*. Not less than 500 kN/m^2.

Table F.3 Thermal conductivity of calcium silicate

Mean temperature (°C)	Thermal conductivity (W/m K)
50	0.055
100	0.058
150	0.063
200	0.069
250	0.075
300	0.083
350	0.092

- *Compressive strength (cold).* Not less than 1300 kN/m^2 load at onset of disruption in the dry state, with a reduction in thickness no greater than 2% under a compressive load of 700 kN/m^2 in the dry state and no greater than 5% under a compressive load of 400 kN/m^2 after 24 h immersion in water.
- *Linear shrinkage.* No greater than 1.6% after 24 h heat soak at 730 °C.
- *Dimensional tolerances.* Tolerances on thickness, length and inside diameter shall conform to requirements of BS 3958: Part 2 or ASTM C533.

F.4 Cellular glass

Cellular glass shall conform to the requirements of ASTM C552 and/or ASTM C240. It is a rigid block material that has been foamed under molten conditions to form a closed-cell structure having properties associated with the lighter-density lower-thermal-conductivity type T4 material, as follows.

- *Rigid cellular glass.* Factory shaped and cut into slabs, radiused and bevelled segments, and half-pipe sections.
- *Density.* Average 120 kg/m^3 ± 10%, measured as per ASTM C303.
- *Thermal conductivity.* No greater than 0.039 W/m K ± 10% at 10 °C, measured as per ASTM C177.
- *Compressive strength.* Average 700 kPa when capped with hot asphalt, measured as per ASTM C165.
- *Chemical requirements.* Less than 10 ppm chloride, when tested in accordance with ASTM C871, and less than 10 ppm fluoride, with a combined halide content no greater than 15 ppm. The material shall be qualified for use on austenitic stainless steel in accordance with ASTM C795 by conforming to the preproduction test requirements of ASTM C692 and the confirming quality control requirements for chemical

analysis of ASTM C871. These standards require 50 ppm sodium silicate content for up to 20 ppm chloride.

- *Water vapour permeability.* Zero measured as per ASTM E96.
- *Linear coefficient of thermal expansion.* $9.0 \times 10^{-6}\ K^{-1}$ as per ASTM E228.
- *Combustibility.* Non-combustible as per ASTM E84.
- *Modulus of elasticity.* 800 MPa, measured as per ASTM C623.
- *Alkalinity.* pH of between 7 and 8 as per ASTM C871.
- *Dimensional tolerance on length.* ±2.0 mm.
- *Dimensional tolerance on thickness.* ±2.0 mm. For pipe sizes up to 450 mm diameter, the tolerances on thickness are in addition to permitted variations in thickness, where these are determined by the manufacturer's economic cutting programme, designed to ensure that the outside diameter of the cellular glass always corresponds to the outside diameter of a standard pipe. This results in thickness variations of +9 mm to –3 mm according to pipe size.
- *Dimensional tolerance on inside diameter.*
  - +1.0 to +2.0 mm for half-shells with inside diameter less than 38 mm.
  - +1.0 to +3.0 mm for half-shells with inside diameter greater than 38 mm.
  - +2.0 to +5.0 mm for segments.
- *Concentricity.* Maximum deviation 3.2 mm or 5% of wall thickness, whichever is the greater.
- *Thickness range.* Minimum thickness of 25 mm and maximum thickness of 120 mm per layer. For thicknesses greater than 120 mm or where the temperature gradient through any individual layer is in excess of 120 °C, multilayer construction shall be used.
- *Length.* All pipe sizes, minimum length, 600 mm.
- *Availability in half-sections.* Insulation shall be supplied as cylindrical sections split into half-sections for all pipe sizes up to 450 mm diameter over insulation. For larger pipe sizes, insulation shall be supplied as radiused and bevelled segments.
- *Fabrication standards.* For all pipe sections fabricated for sizes exceeding 300 mm and not exceeding 450 mm diameter over insulation and for all radiused and bevelled segments, cellular glass may be cut from stacked blocks using a fabrication adhesive and with a minimum number of insulation blocks consistent with economic utilisation of the material. For this purpose each full section of insulation shall contain not more than four 'through' joints, excluding the half-section mating plane. No segment shall as a result of cutting be less than 25 mm thick at the highest point of the arc.
- *Fabrication adhesive.* For jointing of stacked blocks during fabrication of pipe sections, the grade of adhesive to be used for operating

temperatures above ambient shall be a gypsum cement such as Hydrocal B-11.

- *Adhesive coverage.* Fabrication adhesive shall be applied such that there is 100% coverage of adhesive and mating surfaces. In addition, there shall be no visible voids in the adhered joint nor shall any adhered joint exceed 1.6 mm in width.
- *Fabrication facilities.* Shop fabrication of cellular glass pipe sections, segments and fittings shall be prequalified and approved by the fabricator.

F.5 Ceramic fibre paper

Ceramic fibre paper is used for the initial wrapping of piping and equipment containing corrosive fluids and also for similar wrapping of instruments and instrument leads where full contact with steam tracing is not required (classified as light tracing); it shall be a 1.0 mm material in rolls 10 m long and 1.0 m wide, containing a minimal quantity of organic binder.

F.6 Glass rope insulation

Glass rope insulation for wrapping small-bore piping and valves shall consist of unbonded glass fibres enclosed in a braided cover of glass yarn, sufficiently robust to ensure stability during application and in service. The rope shall be resilient and suitable for operating temperatures up to 540 °C.

F.7 Self-setting cement

Self-setting cements are used to join insulation materials into useful shapes. Hydrated silicates are used in conjunction with calcium silicate, perlite and cellular glass to form an intimate mixture of non-asbestos inorganic mineral fibres. These form a general-purpose protective coating suitable for trowel or hand application and with fast-setting properties without the application of heat. The material shall produce a robust surface layer having breather-type weather-resistant properties and being resistant to impact and abrasion damage, with a temperature limit not less than 175 °C for continuous-service conditions. When dried out, the cement shall be free from cracking other than fine hairline cracks.

F.8 Flexible reusable insulation covers

Individually tailored flexible reusable insulation covers for flanged joints, valves and instruments should be shop fabricated in conformance with the following.

- *Outer cover throughout.* Heavy-duty satin-weave fibre-glass fabric silicone rubber impregnated on both sides, completely waterproof, ultraviolet resistant and temperature resistant up to 260 °C (continuous) and having a mass of 560 g/m^2, including 150 g/m^2 silicone.
- *Inner cover up to 260 °C.* Heavy-duty satin-weave fibre-glass fabric, silicone rubber impregnated on one side, water resistant, ultraviolet resistant and temperature resistant up to 260 °C (continuous) and having a mass of 500 g/m^2, including 90 g/m^2 silicone.
- *Inner cover above 260 °C.* High-purity silica fabric of mass 610 g/m^2.
- *Insulation lining.* Unbonded needled type-E glass-fibre matt of 140 kg/m^3 density at 25 mm thickness and having a low chloride level and no resinous or organic binders.
- *Side extensions.* Single-thickness outer cover extensions with heavy-duty drawstrings to effect end closure over adjacent pipe insulation. Drawstrings shall be solid braid Nomex of 4.8 mm diameter, with ends cauterised to prevent ravelling.
- *Protection at hot protrusions.* Double-thickness inner and outer cloth laps to obtain a weather- and heat-resistant seal. Above 260 °C, inner cover material carried over edges with box seams sufficient to ensure integrity of outer cover material whilst remaining weather tight.
- *Retention.* Velcro incorporated at overlaps, and also fully effective easily releasable straps and stainless steel buckles.
- *Sewing thread.* Teflon-coated glass for fabrication up to 400 °C and stainless steel thread above this temperature.

F.9 Preformed rigid polyurethane foam (polyurethane–polyisocyanurate)

- Polyurethane is made by the polymerisation of an isocyanate resin to create a plastic material with a wide range of properties. Reaction between the isocyanate (polymeric methyl diphenyl isocyanate) with certain types of polyol, such as a polyether, creates a tough but rigid plastic material.
- Polyisocyanurate is an improved type of rigid polyurethane. The production process creates strong isocyanurate linkages in the molecular structure. Chemical breakdown of the foam occurs at higher temperatures than polyurethane, and so it is much more difficult to ignite. True polyisocyanurate foam contains about 50% or more isocyanurate linkages.
- The material shall be supplied as slabs, as radiused and bevelled segments and as pipe sections precision cut from fully cured bun stock. The material shall be factory coated with a Mylar or equivalent foil and shall have the following properties.

- *Core density.* Not less than 40 kg/m^3, measured as per ASTM D1622.
- *Thermal conductivity.* Measured as per ASTM C177 on foam 25 mm thick, cut on both sides and aged at 21 °C for 180 days shall be no greater than given in Table F.4.
- *Thermal conductivity.* For freshly blown foam shall be no greater than 0.019 W/m K.
- *Cell structure.* Uniform and free from major voids and bubbles in excess of 1.5 mm diameter across the rise or 5 mm in depth in the direction of rise, and no more than five smaller voids or bubbles per 250 mm × 250 mm area on any cut standard length of half-pipe section, lag or slab.
- *Closed cell content.* Minimum 90% by volume on average with a minimum of 85% by volume for any sample, measured as per ASTM D2856.
- *Compressive strength.* Not less than 160 kPa perpendicular to rise and 240 kPa parallel to rise measured as per ASTM D1621 at ambient temperature.
- *Fire resistance properties.*
  - BS 476 Part 7: Class 1 surface of very low flame spread. ASTM E84. Maximum flame spread rating of 25.
  - ASTM D3014. 85% retention of weight (Butler chimney test).
  - US Bureau of Mines test, flame penetration of 20 min.
- *Linear coefficient of thermal expansion.* (40–80) × 10^{-6} °C^{-1} according to direction as per ASTM E228.
- *Water vapour transmission at 38 °C and 100% relative humidity.* 21.6 µg m/N h measured as per ASTM E96.
- *Alkalinity.* pH of between 7 and 9 as per ASTM C871.
- *Maximum leachable halide content.* 154 ppm as per ASTM C871.
- *Dimensional tolerance on length.* +2.6 mm over 1.0 m length.

Table F.4 Thermal conductivity of preformed rigid polyurethane foam

Mean temperature (°C)	Thermal conductivity (W/m K)
20	0.023
0	0.022
–20	0.024
–40	0.023
–60	0.021
–80	0.019
–100	0.018

- *Dimensional tolerance on thickness.* +1.6 mm for single-layer application and +1.6 mm on the overall thickness of assembled layers for multilayer application.

F.10 Flexible elastomeric foam

Flexible elastomeric foam with a closed-cell structure is manufactured from a natural or synthetic rubber or a combination thereof, in accordance with ASTM C534.

- *Temperature range.*
  - Sheets, from 85 °C to –40 °C.
  - tubes, from 105 °C to –40 °C (high-temperature materials, 145 °C).
- *Density.* 50 kg/m^3, in accordance with ASTM D 1622.
- *Thermal conductivity.* In accordance with ASTM C-177 (Table F.5).
- *Closed-cell content.* 90%, in accordance with ASTM D 2856.
- *Water vapour permeability.* Maximum 0.007 g/m^2 h at 23 °C and 50% relative humidity, in accordance with ASTM E96, procedure A.
- *Mechanical properties.* The dimensional stability of flexible elastomeric foam is not affected by moisture.
- *Chemical properties.* Leachable chlorides content, maximum 90 mg/kg, in accordance with ASTM C871, procedure 2.
- *pH value.* Between 6.0 and 8.0, in accordance with ASTM C 871.
- *Ultraviolet radiation.* Flexible elastomeric foam is not resistant to ultraviolet radiation. This also applies when it is used directly under glass in full light.
- *Combustibility.* Flame spread index less than 25, in accordance with ASTM E84 (locally, different fire requirements may apply).

Table F.5 Thermal conductivity of flexible elastomeric foam

Average material temperature (°C)	Thermal conductivity (maximum)* (W/m K)
20	0.037
10	0.037
0	0.036
–10	0.035
–20	0.034

* Note that these values are based on measurements performed by an independent institute and apply to the field for which the material is used.

Table F.6 Thermal conductivity of ethylene propylene diene monomer

Average material temperature (°C)	Thermal conductivity (maximum)* (W/m K)
40	0.040
20	0.037
0	0.035
–20	0.034
–40	0.030

* Note that these values are based on measurements performed by an independent institute and apply to the field for which the material is used.

F.11 Flexible elastomeric foam (ethylene propylene diene monomer)

Flexible elastomeric foam with a closed cell structure is manufactured from selected synthetic rubber, in accordance with ASTM C534.

- *Temperature range.*
  - Sheets and tubes, from 125 °C to –55 °C.
- *Density.* 60–90 kg/m^3, in accordance with ASTM D 1622.
- *Thermal conductivity.* In accordance with ASTM C177 (Table F.6).
- *Closed-cell content.* 95%, in accordance with ASTM D2856.
- *Water vapour permeability.* Maximum 0.007 g/m^2 h at 23 °C and 50% relative humidity, in accordance with ASTM E96, procedure A.
- *Mechanical properties.* The dimensional stability of ethylene propylene diene monomer is not affected by moisture.
- *Chemical properties.* Leachable chlorides content, maximum 90 mg/kg, in accordance with ASTM C871, procedure 2.
- *pH value.* Between 6.0 and 8.0, in accordance with ASTM C871.
- *Ultraviolet radiation.* Ethylene propylene diene monomer is resistant to ultraviolet radiation and ozone and is weatherproof.
- *Combustibility.* Flame spread index less than 25, in accordance with ASTM E84 (locally, different fire requirements may apply).

F.12 Polyethylene

Polyethylene consists of fillers, in accordance with ASTM C534. The material properties and the thermal conductivity of polyethylene insulation are given in Table F.7 and Table F.8 respectively.

Table F.7 Material properties of polyethylene insulation

Temperature* (°C)	Volumetric mass† (kg/m^3)
20–100	30
20–100	35

* Tested in accordance with ASTM C447.
† Tested in accordance with ASTM D1622.

Table F.8 Thermal conductivity of polyethylene insulation

Temperature (°C)	Thermal conductivity for 35 kg/m^3 material* (W/m K)
40	0.039
20	0.037

* Note that these values are based on measurements performed by an independent institute using ASTM C177.

- *Cell structure.* Minimum closed-cell content of 90%, tested in accordance with ASTM D2856.
- *Water absorption.* 10% by weight, in accordance with ASTM C534.
- *Water permeability.* Tested in accordance with ASTM E96.
- *Water vapour diffusion resistance factor.* 1800, tested in accordance with ASTM E96.
- *Hygroscopicity.* None.
- *Capillarity.* None.
- *Dimensional stability.* In accordance with ASTM C534.
- *Longitudinal shrinkage.* 2%.
- *Diametric shrinkage.* 2%, ultraviolet resistance tested in accordance with ASTM D1171.
- *Leachable chlorides content.* 10 mg/kg, in accordance with ASTM-871.
- *pH value.* pH minimum 6 and maximum 10.5, in accordance with ASTM C871.
- *Combustibility.* Flame spread index less than 25, in conformity with ASTM E84 (locally, different fire requirements may apply).

F.13 Perlite

Perlite granulates (loose fill) consist of expanded perlite, in accordance with ASTM C549. The material properties and the thermal conductivity of perlite are given in Table F.9 and Table F.10 respectively.

Table F.9 Material properties of perlite

Temperature* (°C)	Volumetric mass† (kg/m³)
–272–760	48–72

* Tested in accordance with ASTM C447.
† Tested in accordance with ASTM C520.

Table F.10 Thermal conductivity of perlite

Temperature (°C)	Thermal conductivity* (W/m K)
15	0.049
–50	0.043
–100	0.037
–150	0.031
–200	0.026

* Tested in accordance with ASTM C177.

- *Melting temperature.* 900 °C.
- *Hygroscopicity.* Tested in accordance with ASTM C-390.
- *Compressive strength.* Not applicable.
- *Dimensional stability.* Not applicable.
- *Vibration resistance.* Not applicable.
- *Linear thermal expansion coefficient.* Not applicable.
- *Brittleness.* Not applicable.
- *Ultraviolet resistance.* Not applicable.
- *Leachable chlorides content.* 5 mg/kg, in accordance with ASTM C871.
- *pH value.* pH minimum 6 and maximum 10.5, in accordance with ASTM C871.
- *Combustibility.* Flame spread index zero, in conformity with ASTM E84 (locally, different fire requirements may apply).

F.14 Vermiculite

This is ceramically bonded vermiculite sections, segments and slabs with exfoliated vermiculite as the principal raw material, in accordance with ASTM C516. The vermiculite shall not contain asbestos. The material properties and the thermal conductivity of vermiculite are given in Table F.11 and Table F.12 respectively.

Table F.11 Material properties of vermiculite

Temperature* (°C)	Volumetric mass† (kg/m^3)
400–1000	375 (approximately 10%)

* Tested in accordance with ASTM C447.
† Tested in accordance with ASTM C302.

Table F.12 Thermal conductivity of vermiculite

Temperature (°C)	Thermal conductivity* (W/m K)
800	0.20
600	0.18
400	0.15
200	0.13
10	0.11

* Tested in accordance with ASTM C177.

- *Water absorption.* Tested in accordance with ASTM C209.
- *Compressive strength.* Tested in accordance with ASTM C165.
- *Dimensional stability.* Tested in accordance with ASTM C610.
- *Vibration resistance.* Tested in accordance with ASTM C421.
- *Linear thermal expansion coefficient.* Tested in accordance with ASTM C356.
- *Brittleness.* Tested in accordance with ASTM C203.
- *Leachable chlorides content.* Less than 5 mg/kg, in accordance with ASTM C-871.
- *pH value.* pH minimum 6 and maximum 10.5, in accordance with ASTM C871.
- *Combustibility.* Flame spread index zero, in conformity with ASTM E84 (locally, different fire requirements may apply).

Appendix G
Cladding and jacketing materials

A number of cladding and jacketing materials are available to provide mechanical and weather protection for insulation systems. These are normally classified as metallic or non-metallic materials. Choice is dependent on the availability, application and cost.

G.1 Metallic cladding materials

Commonly used materials include aluminium, aluminised steel, aluminium–zinc-coated steel and galvanised steel.

G.1.1 Aluminised steel sheeting

This consists of steel sheet T2M-300 with an aluminium coating in accordance with ASTM A463M.

- *Aluminium layer thickness.* 300 g/m^2 in total for both sides, 50 mm per side, in accordance with ASTM A463M.
- *Mechanical properties.* 3.1, in accordance with ASTM A463M. The aluminium coating shall not crack, flake or peel during mechanical processing with observance of the minimum deformation radius:
  - Sheet thickness, 0.56 mm; minimum radius, 1 × sheet thickness.
  - Sheet thickness, 0.80 mm; minimum radius, 2 × sheet thickness.
- *Chemical composition.* Commercial quality, in accordance with ASTM A463M, Table 2.
- *Corrosion resistance.* 4.3, in accordance with ASTM A463M.
- *Maximum surface temperature.* 450 °C.

G.1.2 Aluminium–zinc-coated sheeting

This consists of steel sheet provided with an aluminium–zinc alloy layer, in accordance with ASTM A792M.

- Tested in accordance with ASTM A370.
- *Aluminium–zinc layer.* 185 g/m^2 in total for both sides, tested in accordance with ASTM A90 and ASTM A525M.
- *Mechanical properties.* In accordance with ASTM A792M. The aluminium–zinc layer applied shall not crack, flack or peel during mechanical processing with observance of the minimum deformation radius.
    - Sheet thickness, les than 1.25 mm; minimum radius, 1 × sheet thickness.
- *Chemical composition.* In accordance with ASTM A792M.
- *Corrosion resistance.* In accordance with ASTM A792M.
- *Maximum surface temperature.* 315 °C (temperatures above 315 °C cause a colour change; the protective action is retained at temperatures up to 700 °C).

G.1.3 Galvanised steel sheeting

This consists of steel sheet, in accordance with ASTM A527M, and tested in accordance with ASTM A370.

- *Zinc layer.* 275 g/m^2 in total for both sides, tested in accordance with ASTM A525M.
- *Mechanical properties.* In accordance with ASTM A525M. The zinc layer applied shall not crack, flake or peel during mechanical processing with observance of the minimum deformation radius.
    - Sheet thickness, less than 1.25 mm; minimum radius, 3 × sheet thickness.
- *Chemical composition.* In accordance with ASTM A525M.
- *Corrosion resistance.* 4.3, in accordance with ASTM A525M.
- *Maximum surface temperature.* 400 °C.

G.1.4 Stainless steel jacketing

This consists of type 304 stainless steel sheet, in accordance with ASTM A167.

- *Mechanical properties.* Tensile strength, yield strength and elongation, in accordance with ASTM A167.
- *Chemical composition.* In accordance with ASTM A167.
- *Corrosion resistance.* In accordance with ASTM A167 and treated in accordance with ASTM A480M.
- *Maximum surface temperature.* 900 °C (a temperature of 500 °C causes a colour change).

Table G.1 Hardnesses of aluminium sheeting

Type	Temper
Profile or corrugated sheets	H16
Flat rolled sheeting 0.4–0.6 mm thick	H16
Flat rolled sheeting 0.7–1.2 mm thick	H14
Flat sheets	H14

G.1.5 Aluminium sheeting

A number of alternative types of sheeting are available, these include the following:

- Flat sheeting unbacked.
- Flat sheeting with a moisture barrier.
- Profiled or corrugated sheeting.

Aluminium sheeting of the specified thickness and profile shall be 3103 or 5005 alloy to BS 1470, or 3003 or 5005 alloy to ASTM B209 (an acceptable alternative is commercial-grade Alloy 1050), of the hardness listed in Table G.1.

Resistance to mechanical damage is poor and so thicknesses must be increased in order to resist damage. However, the corrosion resistance is relatively high. Aluminium sheeting should not be used for fireproofing because of its low melting point. The maximum surface temperature is 350 °C (a temperature above 150 °C causes structural deformation).

G.2 Non-metallic materials

Plastic materials such as fibre-reinforced plastics and thermoplastic are not commonly used for jacketing because of their low melting temperatures and lack of resistance to mechanical abuse and ultraviolet radiation. However, recent developments have led to the introduction of ultraviolet-cured fibre-reinforced materials which offer improved mechanical resistance and the ability of total containment.

G.2.1 Ultraviolet-cured fibre-reinforced materials

Laminate based on glass-fibre-reinforced polyester resins, which are cured by ultraviolet radiation offer a solution for long-term weatherproofing of insulation.

Table G.2 Mechanical properties of ultraviolet-cured fibre-reinforced materials

Temperature range	0–90 °C
Mass	2 kg/m^2
Bending strength	130 MPa
Tensile strength	50 MPa
Elongation at breaking point	1%
Compression strength	125 MPa
Impact resistance	57 kJ/m^2
Temper	45 Barcol
Layer thickness	1.5 mm
Water vapour permeability*	0.001 g/m^2 h mmHg

* In accordance with the ASTM E96 procedure. If exceeding the indicated value, for application as primary vapour barrier in cold insulation systems only in combination with vapour barrier multiplex foil.

- *Joints.* Watertight joints which resist heavy loads better than any cladding system.
- *Adhesion and strength.* Adhesion and strength at terminations to prevent water ingress and to resist mechanical load.
- *Sealing.* Can also be used to seal metallic cladding, helping to overcome the inadequacies of a metallic cladding system. Adhesion to all types of metal to seal joints in metallic cladding.
- *Material properties.* These are provided in Table G.2.
- *Ultraviolet resistance.* Good.
- *Resistance to (most) chemicals.* Good.
- *Combustibility.* Flame spread index (dry) 20, in accordance with ASTM E84 (locally, different fire requirements may apply). Flame spread index (dry) class 1 in accordance with BS 476. Flash point (flexible material) 32 °C, in accordance with ASTM D93.

G.2.2 Hypalon (chlorosulphonated polyethylene)

Polymeric material based on Hypalon (chlorosulphonated polyethylene) offers a solution for long-term weatherproofing of insulation.

- *Joints.* Watertight joints which resist heavy loads better than any cladding system.
- *Adhesion and strength.* Adhesion and strength at terminations to prevent water ingress and to resist mechanical load.

Table G.3 Material properties of Hypalon (chlorosulphonated polyethylene)

Property	Test method	Typical value
Physical data		
Nominal thickness	—	1 mm
Reinforcing scrim	Glass	6.9 × 3.2
Density	BS 903: Part 1	
Hydrostatic resistance (Mullins burst)	ASTM D751 (method A)	233 lbf/in^2
Breaking strength	ASTM D751 (grab method)	107 lbf
		100 lbf
Elongation at breaking point	ASTM D751 (grab method)	496%
		355%
Tear strength	ASTM D751 (tongue tear)	33 lbf
		34 lbf
Puncture resistance	FTMS 101B (method 2031)	106 lbf
Low-temperature (–40 °F) resistance	ASTM D2136	No cracks
Low-temperature (–40 °F) brittleness	ASTM D746 (procedure B)	No failure
Ply adhesion	ASTM D413 (machine method)	8 lbf/in
Dimensional stability	ASTM D1204 (1 h at 100 °C)	0.5%
Water vapour transmission	ASTM E96 (method BW (No. 2) (7 days))	0.75 g/m^2 per 24 h
Linear coefficient of thermal expansion	ASTM D864	20 × 10^{-5} °C^{-1}

Weathering data		
Ozone resistance	ASTM D1149 (3 ppm at 30% strain at 40 °C for 70 h)	No cracks visible under ×7 magnification
	BS 903: Part A 43 1990	No cracking
	BS 903 part A 23 (400 h minimum)	No deterioration
Accelerated weathering (carbon arc)	ASTM D750	10 000 h No chalking, cracking or crazing No loss of flexibility
Artificial weathering (5000 h = 15 years (Florida) approximately	5000 h under xenon Weather-Ometer	Very slight crazing under ×21 magnification
Artificial weathering	BS 3900: Part F3	1000 h No surface deterioration
Ultraviolet light-fast test	BS 3900: Part F5	1000 h No surface deterioration Rated 4–5 on the grey-scale
Salt spray	BS 3900: Part F12	1000 h No deterioration
Slit water pressure test	DIN 16938–6.3	Waterproof
Aggressive atmospheres test	DIN 500018	Fulfilled
Weather resistance test	SIA 280/9	10 000 h No deterioration
Fire resistance data		
Flame resistance	BS 476: Part 7	Class 1 pass
	BS 476: Part 6	Class 0 pass
	IMO MSC 61 (67) 1996: Part 5	Pass

- *Sealing.* Can also be used to seal metallic cladding, helping to overcome the inadequacies of a metallic cladding system. Adhesion to all types of metal to seal joints in metallic cladding.
- *Material properties.* These are provided in Table G.3.

Appendix H

Use of protection guards

H.1 Design considerations

It is not considered a requirement that all companies at all locations should use one design for personnel protection guards. Much will depend on individual site requirements and the experience and methods that the site's insulation contractors have.

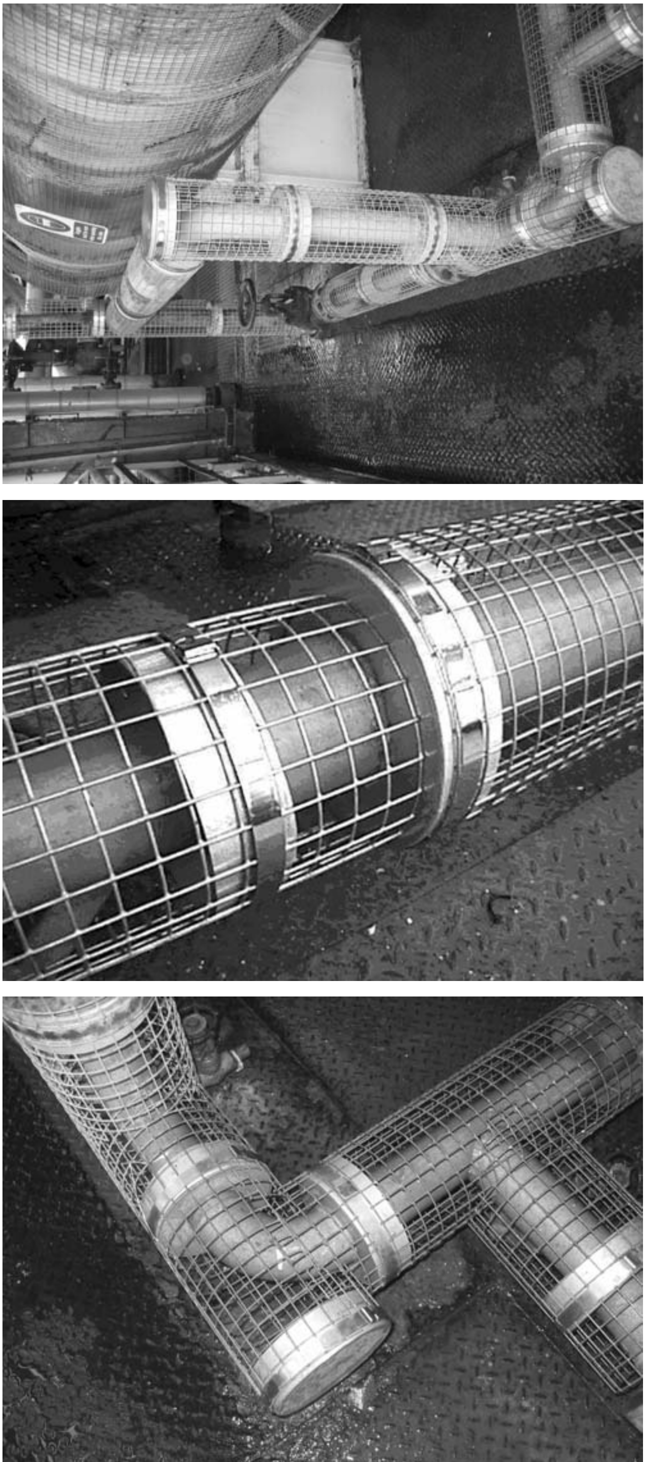
The aim with the personnel protective examples shown in Fig. H.1 is to eliminate the need for welding of supports and to make it a task that the insulation contractors can perform using their traditional tools and skills.

- The flanges were not protected in this installation but could quite easily be if needed. When personal protection is needed on the flanges or valves and easy access is needed for maintenance.
- On higher-temperature applications, or when the metal surface requires greater protection, a fibreglass insulation tape can be applied.

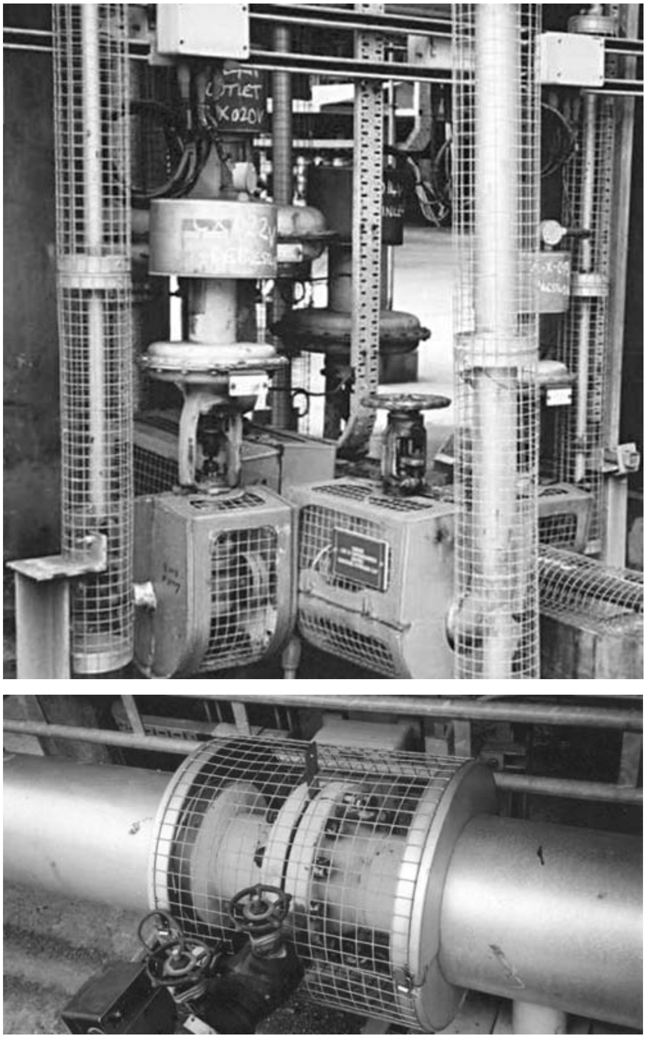
H.2 Method guidance notes

The principles and methods employed for this are very similar to fitting standard insulation cladding. A few noteworthy points are detailed below.

- Spacing of end caps dependent upon the risk of personnel standing or falling on to it.
- Mesh rolled to shape as per normal cladding, 50 mm of overlap allowed.
- Mesh cut to shape using normal cladding patterns.
- 'Stand-off' of mesh from 50 mm pipe.
- Glass-fibre insulating tape can be fitted to the area where end caps make contact to protect pipework and to reduce heat transfer.



H.1 Examples of photographs of personnel protective guarding installations.



H.1 Cont'd

- Care to be taken that end caps are fitted in an orientation that will allow water drainage.
- Sharp edges of cut mesh to be deburred.
- Removable guards can be made using toggle clips.

Appendix I

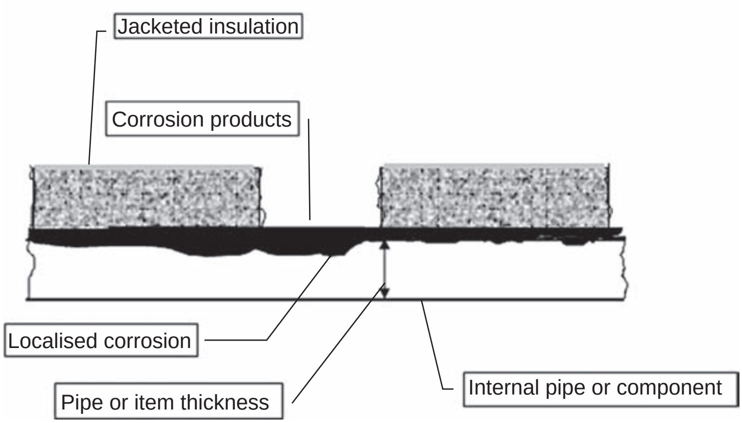
Non-destructive examination and testing techniques

I.1 Visual inspection

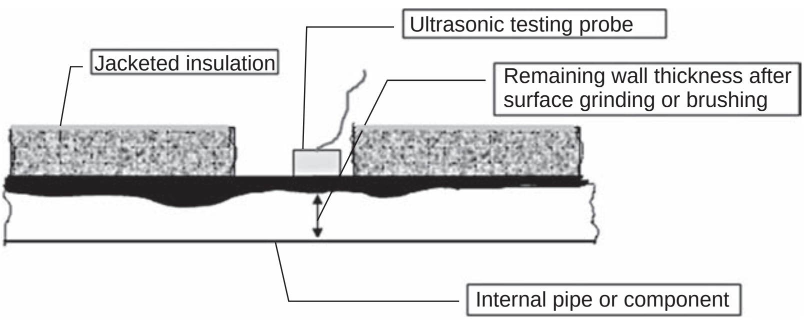
Visual inspection is acknowledged as the best method for determining the presence of CUI on carbon–manganese steels and low-alloy steels. However, it requires removal of the insulation system and is therefore considered to be costly. Normally, the corrosion scale on carbon–manganese steels and low-alloy steels involves an increase in volume and is normally five to ten times greater than the original metal volume loss (Fig. I.1). Absolute quantification of metal loss requires use of a more elaborate NDE or NDT technique. Although visual inspection can be used for determining the presence of CUI on austenitic stainless steels it is not effective in determining the presence of Cl-ESCC.

I.2 Manual ultrasonic thickness measurement through inspection openings

Typically a manual method is used to monitor the internal corrosion of carbon–manganese steel and low-alloy steel equipment using fixed monitoring points to enable periodic multiple-thickness measurements. It can also be used for determining the presence of CUI but is not as effective as measurements conducted from the inside of the vessel, because in part of the limited surface area that is being measured and location points (Fig. I.2). The installation procedures used to make the insulation holes and then to make them water tight with caps or covers is expensive and is often limited to accessible area not always prone to CUI. It is not practical to provide sufficient inspection locations to obtain reliable results. The inspection holes cut in the insulation may also compromise the integrity of the insulation and add to the CUI problem if they are not recovered carefully. This technique will not detect CI-ESCC in austenitic stainless steels with any degree of confidence.



I.1 Visual inspection.



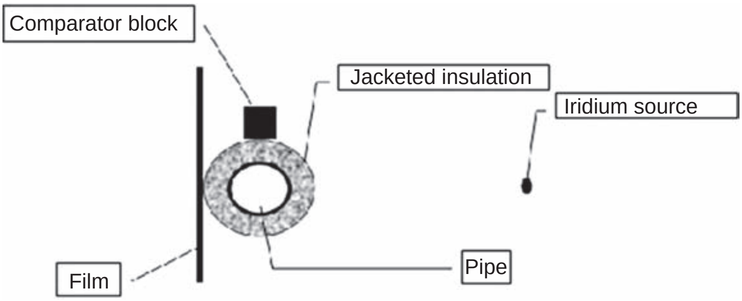
I.2 Ultrasonic thickness measurement.

I.3 Radiography

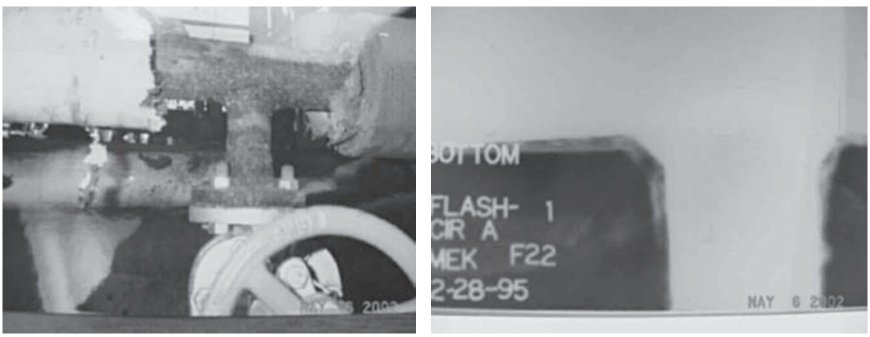
I.3.1 Profile radiography

Exposures are made on small sections of pipe and a comparator block is used to calculate the remaining wall thickness of the pipe. The exposure source is usually iridium 192 (material thickness range, 12–63 mm) and cobalt 60 (material thickness range, 50–150 mm) used for thicker-walled pipes (Fig. I.3). Cobalt 60 is not used offshore.

Profile radiography is an effective evaluation method but it becomes technically challenging in piping systems with a nominal diameter greater than 250 mm (10 in) and only offers limited verification of relatively small areas. Radiation SHE concerns may be overcome by use of small-controlled-area radiography or SafeRad/digital computed radiography. Under some radiographic testing conditions cracking such as SCC can be detected.



I.3 Profile radiography.



I.4 Example of flash radiography.

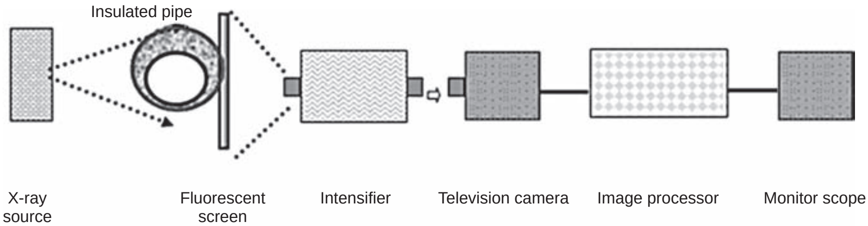
This technique does not detect SCC in stainless steels. In addition, radiation safety can be a concern.

I.3.2 Flash radiography

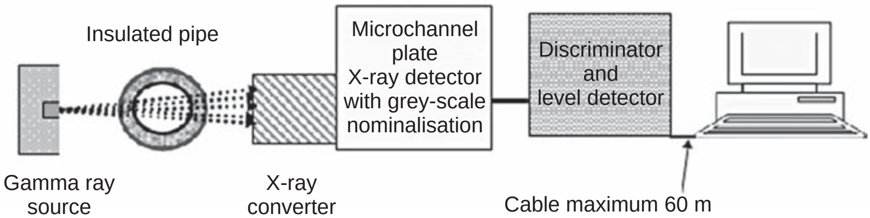
Flash radiography was developed to carry out preventive checks on (insulated) pipelines, vessels and equipment with diameters up to 1 m (Fig. I.4). The radiation source is created by discharging a Marx bank (series of capacitors) into a field emission X-ray tube of low impedance. The pulse of radiation is approximately 30 ns. Fast medical-type film, usually with fluorescent intensifying screens, is often used to produce images from the low radiation flux of the component profile.

I.4 Real-time radiography

There are two categories of real-time radiography (RTR) devices, one using an X-ray source (Fig. I.5) and the other using a radioactive source (Fig. I.6). Two types of instrument are available: the Lixi profiler and the



I.5 Real-time X-ray radiography.



I.6 Real-time gamma-ray radiography.

Image Scope. The Lixi profiler is capable of providing wall thickness information. The Image Scope produces an image of the external profile of the surface under insulation (tangential–profile view). The latest RTR equipment include complementary metal–oxide–semiconductor and gamma scan systems.

Fluoroscopy provides a clear view of the outside diameter of piping, nozzles or equipment (if small enough) through the insulation, producing a silhouette of the outside diameter of a pipe on a television-type monitor that is viewed during the inspection. No film is used or developed.

X-ray digital fluoroscopy equipment operates at a maximum of 75 kV (i.e. a low-level radiation source) but the voltage is adjustable to obtain the clearest image. This allows for safe operation without disruption in operating units or even confined spaces. The radiation penetrates the insulation but not the pipe wall and images the profile of the pipes outside wall. The radiation is generated electrically; so the instrument is perfectly safe when the power is off.

RTR with gamma radiation is a real-time non-contact density measurement system that provides quantitative wall thickness information using gamma absorption from the isotope gadolinium 153. The output of the collimated gadolinium 153 source is directed to a special scintillator. The scintillator electronics contain the equivalent of a low-level X-ray camera. In turn, the scintillator is coupled to a photomultiplier tube whose electronics are matched to the scintillator output. An output signal is sent to the computer which presents a real-time digital strip chart of the component thickness.

I.5 Guided-wave ultrasonic measurements

Guided-wave ultrasonic measurements are used for inspecting piping or small-diameter vessels for internal corrosion as well as CUI. 'Guided waves' are ultrasonic waves guided by the geometry of the object in which they are propagating. The waves are transmitted through the wall cross-section and inspects the entire volume of the pipe, and not solely the surface. Therefore no geometric spreading arises and attenuation is low. The system uses torsional and longitudinal modes. These waves can travel across straight stretches of pipes, bends, supports and welds. The length of piping that can be inspected is dependent on the piping diameter, orientation, complexity, etc. Long straight lengths of piping are easier to inspect with lengths up to 50 m and above achievable.

Only a limited amount of coating or insulation has to be removed to place the probe ring on the pipe and, because of the outside application of the probe ring, the inspection can be carried out while the pipe remains in service. The system has the ability to detect defects in a part of a pipe that is buried or inaccessible, dependent on coating. A probe ring placed around the pipe transmits guided waves through the pipe in either direction of the probe ring. The pulse-echo-type operation provides information on feature position and approximate size. The interpretation of results is performed with sophisticated analysis aids.

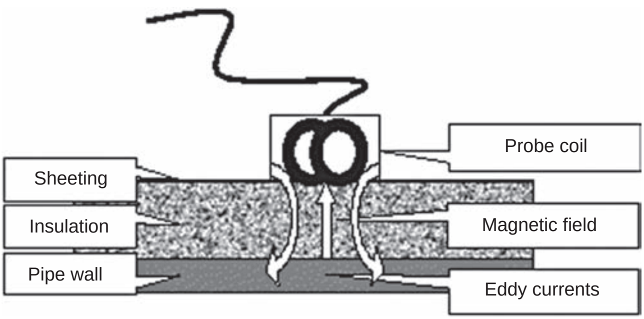
I.6 Pulsed-eddy-current technique

The pulsed-eddy-current technique is capable of being used 'on-stream' and it measures the average remaining wall thickness of ferromagnetic material through an insulation layer.

The measurements with the pulsed-eddy-current technique are based on the phenomenon that, in materials that are conductive, eddy currents are induced when subjected to a variable magnetic field (Fig. I.7).

The strength of the induced magnetic properties are generally greater than the intrinsic magnetic propeties of a given material. The magnetic field used for the measurements is generated by means of a (transmitter) induction coil system. The coil is placed directly on to the surface of the insulation sheeting at the location to be measured.

During a defined time a direct current is sent through the coil, causing a stable magnetic field in the pipe or vessel wall. After switching off the



I.7 Pulsed-eddy-current induction.

current, the magnetic field drops rapidly to zero. This generates eddy currents within the material under examination. The duration of the eddy currents within the enclosed magnetic field is directly related to the thickness of the material. The strength of the magnetic field and the eddy currents has no influence on the duration of the eddy currents.

The strength and the measurable duration of the eddy currents depend on the strength of the magnetic field as well as on the conductivity and permeability of the material. If the strength and duration are measured, the average wall thickness can be calculated. A pulsed eddy current can be used on the flat surfaces of a piping or equipment but corrosion is more likely to occur around nozzle welds, etc., where the eddy current technique cannot be used because of geometric restrictions.

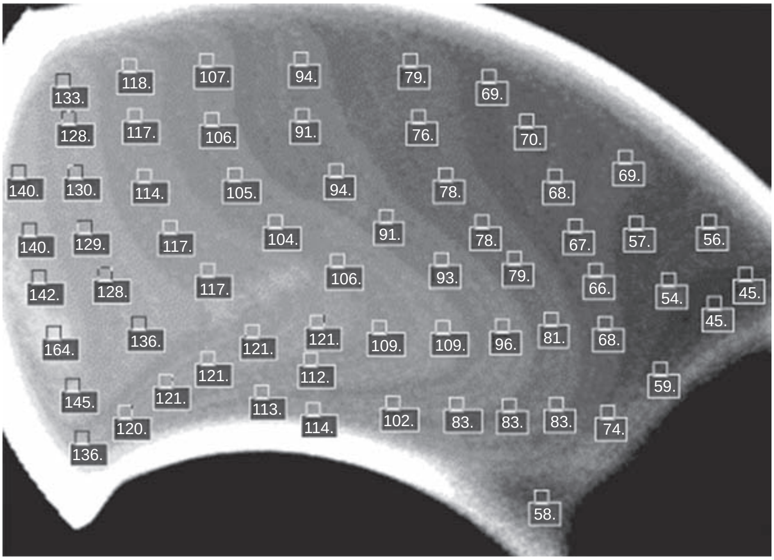
I.7 Digital radiography

Digital radiography can highlight CUI and provide a measurement of material loss. The measurement sensitivity is dependent on a number of variables. These include exposure conditions, image quality requirements and productivity. As with conventional radiographic film techniques, digital radiography exhibits a wide range of resolutions, speeds and throughput capabilities (Fig. I.8).

The image quality of radiographic devices to achieve different levels of radiographic sensitivity, speed and throughput, targeted to different applications includes the following.

- Film digitisation.
- Storage phosphor computed radiography.
- Digital radiography.

The performance characteristics of these systems can help to determine the right method for application.



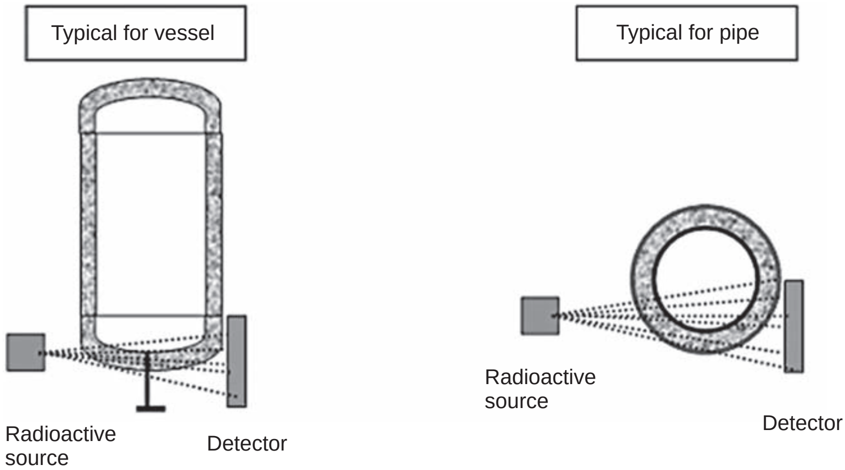
I.8 Digital radiography of an elbow.

- Resolving capability and penetrameter sensitivity.
- Although radiographers are familiar with penetrameter sensitivity through the use of image quality indicators, the resolving capability is not generally measured. A procedure has been developed through HOIS 2000 employing EN 1435.
- At present, an NDE and NDT standard for measuring resolution does not exist, although there are well-established standard methods for evaluating a system's resolving capability.
- Material thickness or loss for any given point.
- Average thickness or loss over any given area.

I.8 Infrared thermography

Infrared thermography is not designed to detect CUI but, under the right conditions, it can be used to detect damp spots in the insulation, because there is usually a detectable temperature difference between the dry insulation and the wet insulation (Fig. I.9). Corrosion is a distinct possibility in the areas beneath the wet insulation.

Infrared thermography has already been successfully used for a number of years in 'energy conservation' surveys where defects in insulation manifest themselves as hot or cold spots on the surfaces. These defects can be caused either by bad fits or by subsequent damage caused to insulation due



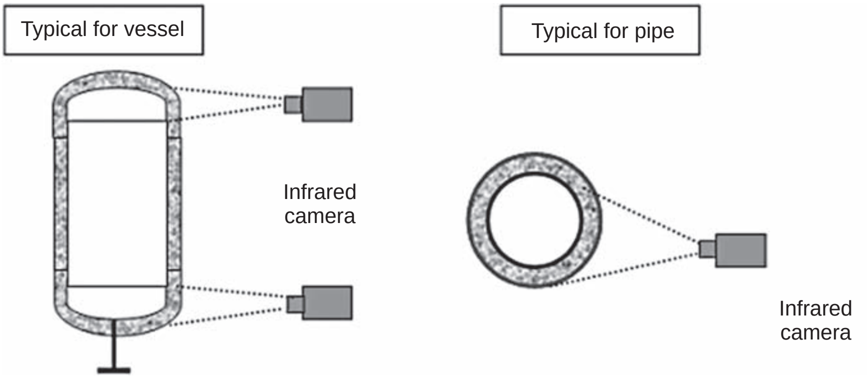
I.9 Infrared thermography system.

to water ingress. Although wet insulation does not necessarily mean that corrosion is taking place, it is a good indication of where problems may eventually develop and, therefore, such defects should be eliminated as soon as possible.

- It is used for screening.
- Qualitative assessment of relative temperature at insulation is provided.
- CUI indicator is a temperature gradient caused by water (however, there could be other causes of gradients).
- Applications are similar to those for neutron backscattering.
- It is used for pipe and vessels.
- Follow-up with a technology to assess corrosion directly is required.
  - For example, RTR is a good supplement.

I.9 Neutron backscattering

Neutron backscattering is also not designed to detect CUI directly, but the technique does identify areas of wet insulation on pipes and vessels which may be possible areas of CUI. A radioactive source emits high-energy neutrons into the insulation. If there is moisture in the insulation, the hydrogen nuclei attenuate the energy of the neutrons. The instrument's detector is only sensitive to low-energy neutrons. The neutron count displayed by the detector is proportional to the amount of water in the insulation. Low counts per time period indicate a low moisture content (Fig. I.10).



I.10 Neutron backscattering system.

(The detector and source are housed in the same enclosure, i.e. the reflected or backscattered neutrons are detected.)

I.10 Dye penetrant testing

Dye penetrant testing is utilised mainly for austenitic stainless steel after the insulation has been removed. Normally, if chlorides are present from chloride containing water or from the insulation material itself, it is possible to initiate SCC in welds or at the bottom of external pitting in material.

Appendix J

Case studies

Appendix J is a compilation of a small selection of CUI case studies which represent the broad nature of the problem. A standard reporting template has been used in order to allow users of the document to easily complete and build their own portfolio of CUI failures. The case studies are taken from 'hot' environments and cover issues with both carbon steel and stainless steel equipment, piping and vessels. The failures are primarily due to failings when originally commissioned due to poor design details and installation procedures and exacerbated by poor maintenance programmes.

J.1 Case study 1

- *Duty.* Fluid catalytic cracking unit feed drum.
- *Material.* Carbon steel.
- *Wall thickness.* 12.7 mm.
- *Loss of wall thickness.* This occurred as a result of a through-wall crack.
- *Date of commissioning.* 1985.
- *Period of metal loss.* 21 years.
- *Metal loss identification method.* Inspection.

J.1.1 Description of corrosion mechanism or detail

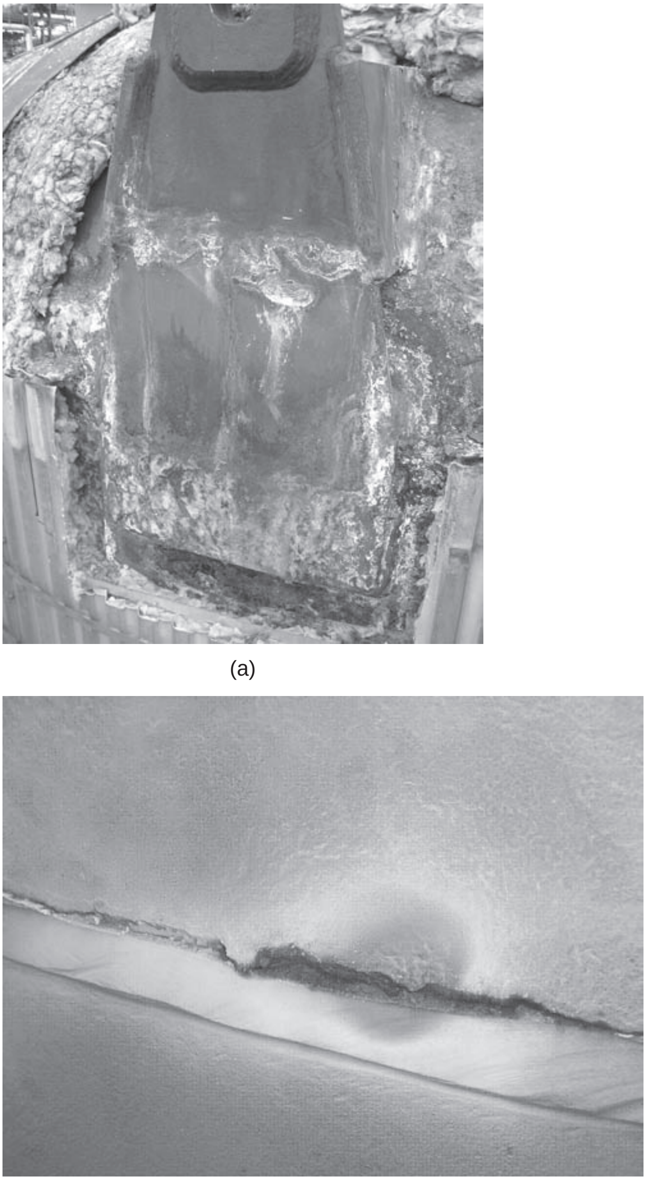
The fluid catalytic cracking unit feed drum (Fig. J.1(a) and Fig. J.1(b)) operates at 193 °C (380 °F) which is above the recommended temperature for CUI. The lifting lugs had been left on the vessel at installation and not totally encapsulated in cladding. Severe corrosion was experienced behind the lifting lug, which acted as a heat sink, lowering the temperature locally to below 150 °C. The CUI products forced the lifting lug away from the vessel, causing a through-wall crack on the top head.

J.1.2 Action taken

Lifting lugs were removed and the vessel repaired. Full paint coating and insulation were reinstated.

J.1.3 Lessons learned and design change

Remove lifting lugs after installation. If it is necessary to keep the lifting lugs, then fully encapsulate them in cladding.



(a)

(b)

J.1 Case study 1.

J.2 Case study 2

- *Duty.* Sour water stripper tower.
- *Material.* Carbon steel with stainless steel cladding.
- *Wall thickness.* 12.7 mm.
- *Loss of wall thickness.* Unknown.
- *Date of commissioning.* 1985.
- *Period of metal loss.* 21 years.
- *Metal loss identification method.* Inspection.

J.2.1 Description of corrosion mechanism or detail

The sour water stripper tower operates at 125 °C (255 °F) at the bottom of the tower and 80 °C (180 °F) at the top of the tower.

Figure J.2(a) shows a section of a lower support ring which has virtually corroded through (22 mm); the shell also showed losses of 3–4 mm. Figure J.2(b) shows that a section of the tower just below top head experienced severe CUI and indicates 50–75 mm of corrosion products (10 mm thick). On the right-hand side of the photograph is the exposed internal stainless steel cladding.

J.2.2 Action taken

The support ring was cut out and replaced. The shell of tower was locally weld repaired. The top of the tower was replaced.

J.2.3 Lessons learned and design change

Regular inspection of cladding integrity is required. The top head cladding was in an extremely poor condition.

(a)

(b)

J.2 Case study 2.

J.3 Case study 3

- *Duty.* Amine knock-out drum.
- *Material.* Carbon steel.
- *Shirt thickness.* 10 mm.
- *Loss of wall thickness.* 10 mm.
- *Date of commissioning.* 1978.
- *Period of metal loss.* 28 years.
- *Metal loss identification method.* Inspection.

J.3.1 Description of corrosion mechanism or detail

The knock-out drum (Fig. J.3) operates at about 27 °C (80 °F).

There is severe corrosion of the skirt, up to 10 mm loss, and full-wall-thickness metal loss.

J.3.2 Action taken

Repaired and refireproofed.

J.3.3 Lessons learned and design change

Continued inspection of fireproofing is required.

J.3 Case study 3.

J.4 Case study 4

- *Duty.* Steam condensate line.
- *Material.* 304 stainless steel.
- *Wall thickness.* Unknown.
- *Loss of wall thickness.* None.
- *Date of commissioning.* Approximately 1980.
- *Period of metal loss.* Unknown.
- *Metal loss identification method.* Other.

J.4.1 Description of corrosion mechanism or detail

The aluminium wrapping was damaged when the clamps were fixed during the installation of the line (Fig. J.4).

The refinery is located close to the sea and the air holds trace amounts of salt.

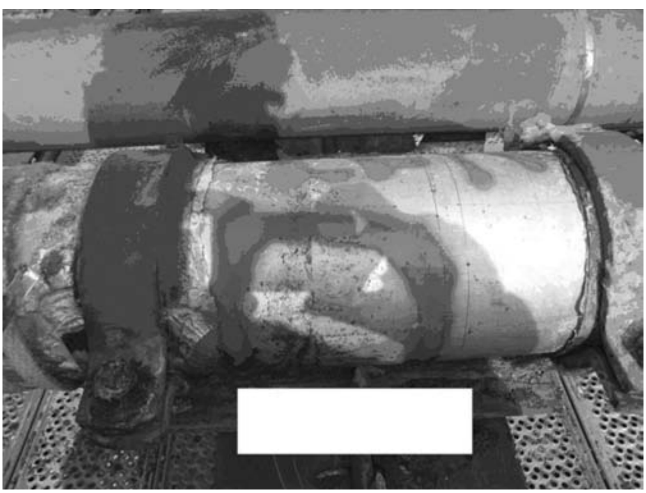
The rainwater containing trace amounts of salts could leak through the insulation and aluminium wrapping and finally caused Cl-ESCC. The operation temperature of the line is approximately 100 °C.

J.4.2 Action taken

The steam condensate line was repaired.

J.4.3 Lessons learned or design change

Extra care should be taken not to damage aluminium wrapping during installation and insulation.



J.4 Case study 4.

J.5 Case study 5

- *Duty.* 4 in gas compressor recycle.
- *Material.* Carbon steel.
- *Wall thickness.* Schedule 40s.
- *Loss of wall thickness.* None.
- *Date of commissioning.* Unknown.
- *Period of metal loss.* Localised.
- *Metal loss identification method.* Other.

J.5.1 Description of corrosion mechanism or detail

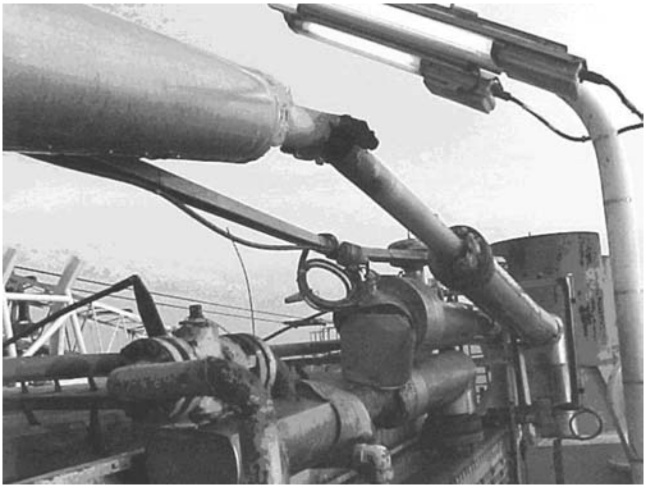
A 4 in recycle line on the gas compressor recycle line (Fig. J.5) ruptured, releasing the contents of the compression system to the atmosphere. The released gas was detected by an infrared beam detector located on the roof, which initiated automatic production shutdown and depressurisation. The gas did not ignite and was quickly dispersed from the roof. The platform went to muster and was stood down 2 h later once the failed line had been made safe. No one was hurt or injured.

J.5.2 Action taken

The recycle line was replaced.

J.5.3 Lessons learned and design change

All piping systems should be included in RBI schedules.



J.5 Case study 5.

J.6 Case study 6

- *Duty.* Hydrocarbon tank.
- *Material.* Carbon steel.
- *Wall thickness.* 6.0 mm nominal.
- *Loss of wall thickness.* 4–5 mm.
- *Date of commissioning.* Unknown.
- *Period of metal loss.* Localised.
- *Metal loss identification method.* Insulation strip.

J.6.1 Description of corrosion mechanism or detail

A tank has been totally delagged and significant CUI losses have been seen at various random locations on the shell plates (Fig. J.6(a), Fig. J.6(b) and Fig. J.6(c)). This tank is a good example of how random CUI can occur on equipment, i.e. losses in the middle of plates as well as at seam weld areas.

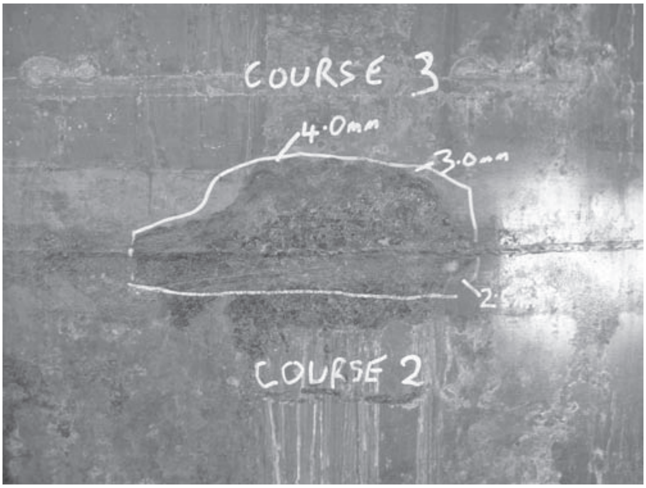
No losses were observed at the ladder support brackets, or at the single insulation support ring at the bottom of the shell.

J.6.2 Action taken

The tank was repaired.

J.6.3 Lessons learned and design change

Storage tanks are normally challenged extensively regarding fully delagging owing to the high cost, but in this case the unit accepted a full delag on the basis that the cladding had slipped at the top kerb angle and this would have led to water ingress and potential CUI.



(a)

(b)

(c)

J.6 Case study 6.

J.7 Case study 7

- *Duty.* 30 in methane piping.
- *Material.* Carbon steel.
- *Wall thickness.* 37.5 mm.
- *Loss of wall thickness.* 4–5 mm.
- *Date of commissioning.* Unknown.
- *Period of metal loss.* Localised.
- *Metal loss identification method.* Insulation strip.

J.7.1 Description of corrosion mechanism or detail

There was localised CUI on 30 in methane piping (Fig. J.7(a) and Fig. J.7(b)). The operating temperature was 32 °C at 72.5 barg.

J.7.2 Action taken

The piping was not reinsulated after painting.

(a)

(b)

J.7 Case study 7.

J.8 Case study 8

- *Duty.* 2 in natural gas piping.
- *Material.* Carbon steel.
- *Wall thickness.* 4.0 mm nominal.
- *Loss of wall thickness.* 2.5–3.0 mm.
- *Date of commissioning.* Unknown.
- *Period of metal loss.* Localised.
- *Metal loss identification method.* Non-intrusive inspection.

J.8.1 Description of corrosion mechanism or detail

There was localised CUI on 2 in natural gas piping (Fig. J.8(a) and Fig. J.8(b)). The operating temperature was 26 °C at 26 barg, and the corrosion allowance was 1.0 mm.

J.8.2 Action taken

The estimated remaining wall thickness was too low to risk chipping, owing to the risk of perforation.

Profile radiography was carried out (Fig. J.8(c)) and the lowest remaining wall thickness measured from radiographs was 1.5 mm. Allowing for limitations of the radiographic technique and the NDE tolerance, the minimum remaining wall thickness is considered to be 1.0 mm on both the pipe and the flange sides of the weld.

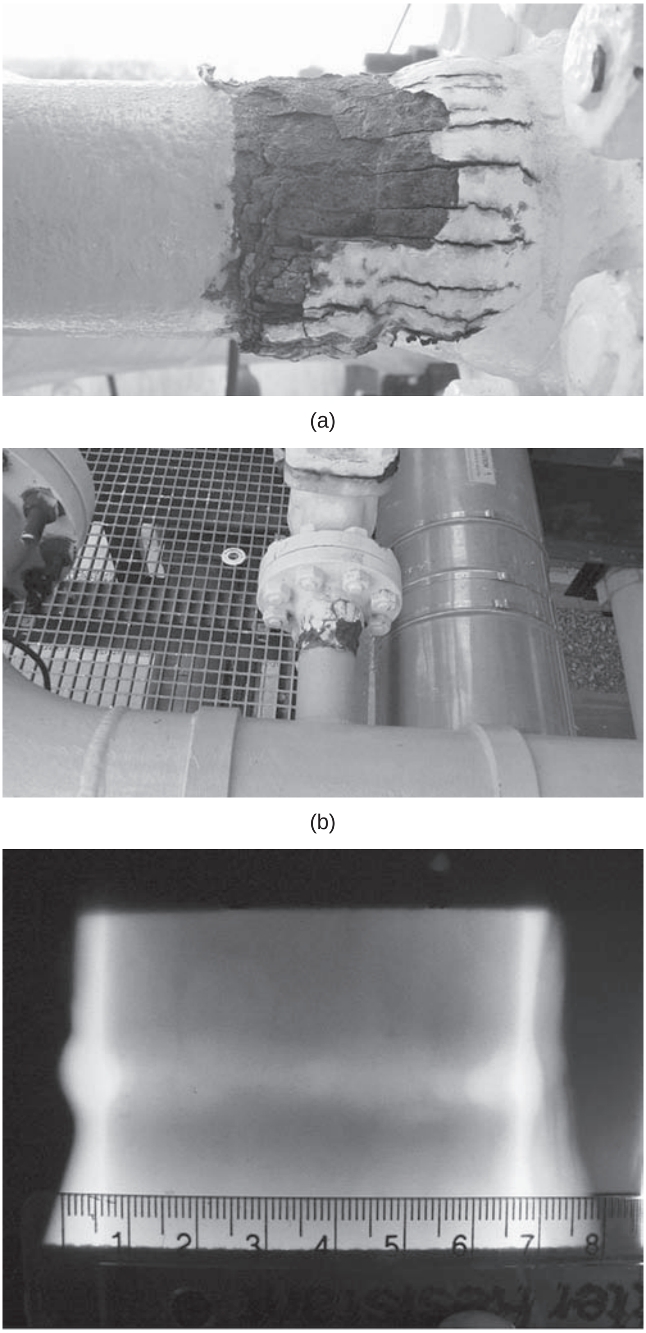
From the eight radiographs taken around the circumference it was apparent that 50% of the pipe circumference still had approximately 2.0–2.5 mm remaining wall thickness.

J.8.3 Lessons learned and design change

The gas piping was not reinsulated after painting.

The need for insulation should be challenged.

Ideally the line should be depressurised prior to any corrosion scale removal.



(a)

(b)

(c)

J.8 Case study 8.

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