Corrosion and Materials in Hydrocarbon Production

A Compendium of Operational and Engineering Aspects

Bijan Kermani and Don Harrop

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To our families

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Preface

Government policy in the pursuit of a carbon-neutral world economy has been a commitment adopted by an increasing number of industrial nations. However, for the foreseeable future, fossil fuels in which hydrocarbons will play a significant role are likely to remain the primary source of energy.

There is a continuing drive to increase the life of existing oil and gas field developments through a number of avenues. These include, for example, tie-backs from nearby smaller reservoirs, otherwise uneconomic to develop alone, and by increasing the recovery rate from existing fields. The average commonly reported recovery rates after primary (natural flow under existing reservoir pressure) and secondary (e.g. water injection, hydraulic fracking) enhancement operations for oil are between 35% and 45%. This could potentially be increased in certain reservoirs by a further 5–15% through tertiary recovery methods (e.g. reducing reservoir oil viscosity by CO_2 flooding, steam, or surfactant injection). Nevertheless, there remains a continuing search for new economic sources of hydrocarbons, taking exploration activities into harsher environments through deep high pressure/high temperature (HPHT) wells, into geographically remote and/or increasing environmentally sensitive areas and deep water. This enterprise has created increased challenges: (i) to the economics of project development and field operations; (ii) on the performance envelope of existing oilfield technology; and (iii) in meeting Health, Safety and Environment (HS&E) commitments which can impact the Licence to Operate (LTO). Ensuring the mechanical integrity of facilities is therefore paramount. The accurate prediction of materials' performance and their optimised selection in tandem with pro-active corrosion mitigation are primary considerations at design and throughout a field's operating life.

Hydrocarbons-producing facilities and infrastructures are potentially subject to both external and internal corrosion threats; in the case of the former from hostile and geographically remote operating environments, and in the latter from the presence of wet produced fluids and acid gases. Both these threat types impact materials selection, engineering design, and through life integrity management (IM).

Corrosion in its various forms remains a major potential threat to successful hydrocarbons production and its optimum control and management are essential to the cost-effective design of facilities and their safe operations. Its impact can be viewed in terms of effect on capital and operational expenditure (CAPEX and OPEX) and HS&E and associated process safety risks. It is, therefore, essential to have a sound corrosion design and management philosophy for production facilities to safely handle and transport wet hydrocarbons enabling integrity assurance and trouble-free operations. Such a philosophy can be used in the technical/commercial assessment of new field development and in prospect evaluation, to prolong the life of ageing assets and, for handling sour fluids by facilities not normally designed for sour service. The book sets out to provide such a philosophy in a pragmatic manner.

The book is intended to be suitable for both practising materials and corrosion engineers working in hydrocarbons production as well as those entering the area who may not be fully familiar with the subject. It is not a textbook; rather it is a practical manual/ready reference source to steer design and operations engineers to currently established best practice drawn on the many years' global experience of the book's authors and contributors. It embodies over 500 years of cumulative field and engineering experience.

The primary focus is on operational and engineering aspects by capturing the current understanding of corrosion processes in upstream operations and providing an overview of the parameters and measures needed for optimum design of facilities. Emphasis is placed on material optimisation which is structured by presenting user-friendly roadmaps. The book is intended to act as an applied tool focusing on engineering features of corrosion and materials.

Chapters on internal corrosion address: the types and morphology of corrosion damage; the principal metallic materials deployed; and mitigating measures to optimise its occurrence. Chapters on external corrosion address corrosion under insulation (CUI), external coating systems and cathodic protection (CP). In addition, a chapter has been assigned to systematically quantifying the level of in-service risk of corrosion, presented in terms of likelihood and consequence, in order to prioritise operational risk. Together with a broader overview of corrosion and integrity management, outlined is a structured and performance-managed approach to the provision of safe and trouble-free operations through an integrated cross-discipline methodology and approach. This is an integral part of meeting compliance with HS&E requirements and legislation and risk management: a primary purpose behind the broader remit of IM.

The book captures and provides solutions via four principal avenues for upstream hydrocarbon operations from reservoir to the refinery and petrochemical plants:

1) Outlining key corrosion threats, both internal and external, and means of inspection, monitoring, control and management.
2) Providing necessary background on types and nature of materials used for the construction of CAPEX-intensive facilities.
3) Underlining current and future challenges that the industry sector is facing with some steer towards respective management and technical solutions.
4) Implementation of effective and progressive materials optimisation, corrosion mitigation methods and corrosion and integrity management strategy.

The final chapter considers the future outlook in energy demand and supply, translating these into technology challenges facing the hydrocarbon production industry sector, which in turn shapes the materials and corrosion technology themes necessary to deliver business success and continuously improve safety, security, and minimise impact on the environment.

It should be noted that there is never a single answer to a potential challenge. The solution may invariably be drawn from a number of options, the convergence of which can lead to an optimum outcome. It is against this background that the book is compiled, allowing flexibility in choice having considered all *credible* corrosion threats and their respective mitigation. The importance of failure analysis in allowing lessons to be learnt is highlighted, together with the importance of in-house, national and international standards in effective implementation of corrosion management and strategy.

Acknowledgement

The book represents much more than merely a compilation of individual experience and thinking on selected topics. The authors would like to express their appreciations to all who have contributed their time and effort to ensuring its successful completion. The authors wish to acknowledge the significant inputs from:

Dr Michel Bonis (France) and particularly in relation to the chapter on Microbial Corrosion.
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Contributions from a number of individuals in relation to their steer in setting the focus and comments on specific chapters or elements are very much appreciated. These include Dr Ed Wade (UK) and Dr Bruce Craig (USA). Notably, Dr Wade made positive and constructive comments and corrective suggestions on many themes considered vital in moving forward. And contributions from Professor Ali Mosleh (USA) and Mr Mehdi Askari (Iran) in reviewing selective chapters and their valuable comments are acknowledged. Provision of a few photographs by Mr Matt Dabiri (US) is highly appreciated.

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Bijan Kermani
Don Harrop

1 Introduction

In the search for new sources of oil and gas, operational activities have moved to harsher environments in deeper high pressure/high temperature wells, remote areas, and deep-water regions. These have created increased challenges for the economy of project development and subsequent operations whereby the integrity of the facilities, optimisation of the materials, and accurate prediction of the materials' performance are becoming paramount. In addition, the economic moves towards multi-phase transportation through sub-sea completions and long infield flowlines have a tendency to increase the risk of corrosion threats, thus placing a heavier duty on integrity management in upstream operations.

Corrosion potentially presents many threats, in many forms, and remains a major operational obstacle to successful hydrocarbon production. These threats have wide-ranging implications for the integrity of many materials used in the upstream petroleum industry, thus affecting capital expenditure (CAPEX) and operating expenditure (OPEX), with consequences on health, safety, and the environment (HS&E). Furthermore, if not effectively identified and managed, in extreme cases, corrosion may have major business implications, such as disruption to production, financial penalties, adverse societal publicity, and even an impact on the Licence to Operate (LTO). However, corrosion mitigation and control by measures through national and international corrosion communities have led to significant improvements in the provision of safety and security and enhancing public welfare.

This chapter sets out to outline three subject areas with a common thread of describing the content of the book and its scope in relation to upstream hydrocarbon production. The subject areas are:

1) the impact of corrosion, highlighting its economic implications;
2) types of corrosion threats in oil and gas production and transportation, the manner in which they manifest, and the means of their control and design;
3) where future priorities need to be set to sustain and develop the continuing fitness-for-purpose of the practice and status of the corrosion and materials discipline.

In addition, brief reference is made to the image of the potential corrosion disciple with a view to outlining future priorities to attract a new generation of high calibre professionals to this field.

Corrosion and Materials in Hydrocarbon Production: A Compendium of Operational and Engineering Aspects, First Edition. Bijan Kermani and Don Harrop.

1.1 Scope and Objectives

This book aims to produce a practically driven reference guide to assist corrosion and materials engineers in their quest to select and optimise the most appropriate and economical choice of material and corrosion control strategy for upstream operations.[1] It covers measures and mitigation methods to address corrosion threats in hydrocarbon production systems carrying hydrocarbons, injection water, and/or produced water.

In particular, the book provides an understanding of the primary subject areas that affect the continued and trouble-free operation of hydrocarbon production facilities. It provides a compendium of the principal considerations, current best practice, and key issues associated with each theme without going into absolute detail which will be specific to each individual application.

The focus primarily is on the following topics:

1) Corrosion threats and their respective assessment practices and mitigation methods.
2) Corrosion interrogation methods, including monitoring and inspection data capture and full analysis.
3) Methods by which materials are selected for a particular application.
4) Determining corrosion risk and implications with respect to defining safe operational conditions and the implementation of mitigation methods, measures and practice as an integral part of a fit-for-purpose corrosion and integrity management strategy.
5) Consideration of current and future challenges to those engineers who wish to specialise in materials and corrosion knowledge, and outlining the gaps in best implementation of know-how and knowledge.

While the majority of subject areas relate to addressing internal corrosion, cases of coatings, corrosion under insulation (CUI), cathodic protection (CP), and corrosion trending, combining data generated from corrosion monitoring and inspection, are also included to complement mitigation methods.

The book is intended for use by both competent engineering personnel working in upstream production operations who have knowledge and experience of dealing with corrosion and materials as well as those entering the area who may not be fully familiar with the subject.

1.1.1 Contents of the Book

A summary of the themes and subject areas covered in this book is presented in Figure 1.1.

1.2 The Impact of Corrosion

The impact of corrosion can be viewed in terms of its effect on CAPEX, OPEX, and HS&E. In the past few decades there have been significant studies in various parts of the world on the cost of corrosion and how it affects a country's economy.

According to the current US corrosion study, the direct cost of metallic corrosion is $276 billion on an annual basis. This represents 3.1% of the US gross domestic product (GDP) [1].

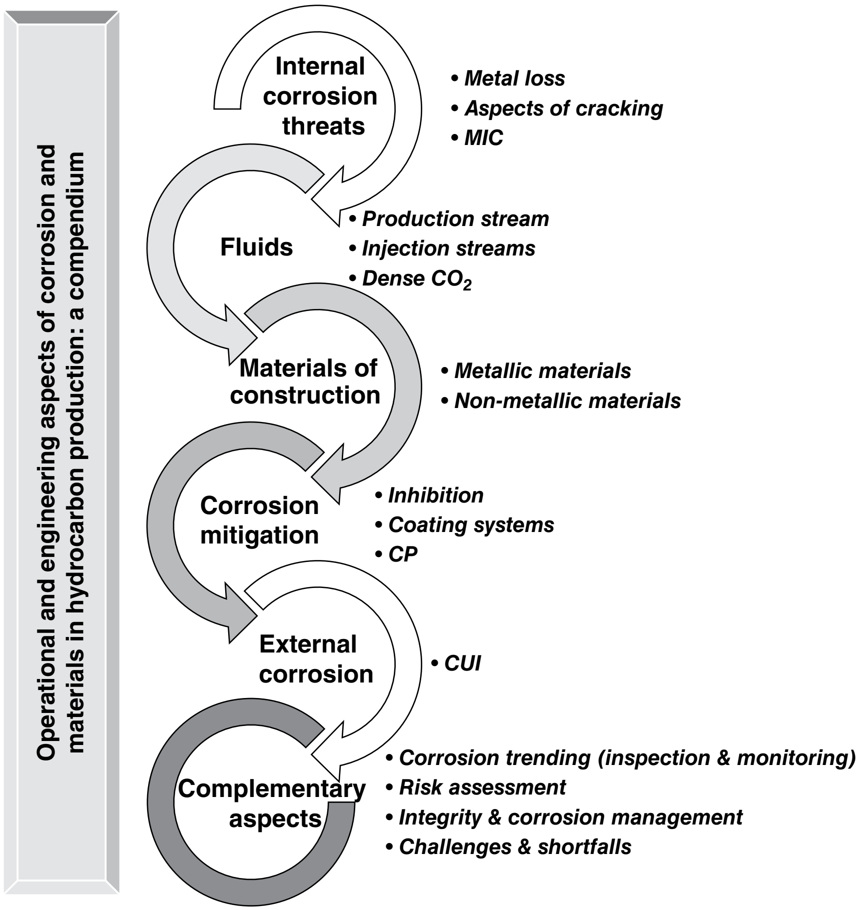

Figure 1.1 The overall themes and subject areas discussed in this book.

The 2016 IMPACT [1] study, released by NACE International, indicates that there are problems with using the existing studies to examine savings over time due to the implementation of corrosion control practices. For instance, in the US, the cost of corrosion was estimated to be equivalent to 2.5% of GDP in 1949 (using the Uhlig method), 4.5% of GDP in 1975 (using the input/output method), and 3.1% of GDP in 1998 (using the Hoar method). The problem is that, in general, these studies use different analyses to estimate the cost of corrosion, so a direct comparison is not possible. Nevertheless, the overall cost of corrosion has been estimated to be between 2% and 5% of GDP, depending on the region of the world, which may be due to differences in methodology. Irrespective of the overall economic impact, the important point is that the cost of corrosion has not actually changed with time, knowledge, or technology since it was first looked at by Uhlig. Therefore, it needs to be reiterated that the use of economic impact alone has limited influence on the interest in raising the importance and funding of corrosion with management.

Domestic oil and gas production is considered a stagnant industry in the US because most of the significant available reserves have been exploited – although the growth in shale gas exploration and production may well change this view. Direct corrosion costs associated with conventional production activity were determined to be about $1.4 billion, with $0.6 billion attributed to surface piping and facility costs, $0.5 billion to downhole tubing, and $0.3 billion to CAPEXs related to corrosion [1]. The NACE 2016 IMPACT [1] study provides valuable tools for companies to implement an effective Corrosion Management System Framework, benchmark their current practices with other organisations worldwide, and learn how to optimise the safety and lifetime of critical assets.

While the overall cost impact of corrosion measured against GDP provides a benchmark for all industrial sectors, a measure focused specifically on hydrocarbon production was needed. To do this, many studies have focused on making the overall cost impact specific and tangible in terms of lifting cost per barrel equivalent. These studies have come up with a consensus view that corrosion failures, the majority of which are related to metal loss CO_2 and H_2S corrosion and cracking threats, account for some 25% of all safety incidents – affecting 2.8% of turnover and 2.2% of tangible assets – resulting in a 8.5% increase on CAPEX, 5% of lost/deferred production, and 11.5% increase to the lifting costs. These are estimated figures and dependent on the operator and region, obtained from a number of publications [2]. They are estimated as the additional corrosion management costs necessary to successfully deploy carbon and low alloy steels (CLASs) as the appropriate construction materials.

The spread of these figures is highly dependent on the manner in which a corrosion control philosophy is planned and implemented, as they vary according to type of operation, location, and operator. The estimated cost of corrosion is put between US$0.3–0.9 (or even higher depending on the conditions and region) for the production of each barrel of oil equivalent (boe) [1–4].

It is outlined by the 2016 IMPACT study that some 10–30% of this cost can be reduced by implementing currently available corrosion control best practices [1]. However, the overall financial impact continues to place heavy penalties despite concerted efforts by the corrosion and materials community. This is primarily due to the increasing move to harsher production conditions and the extended use of CLASs beyond what was previously considered feasible. In addition, while limited, some costly failures have occurred, mainly due to lack of understanding of anticipated exposure conditions or inadequate metallurgical treatment of components, and are discussed in Chapter 19.

1.2.1 The Overall Financial Impact

Several publications are available, describing the financial impact of corrosion in detail. Putting these in context, it can be estimated that with a daily global hydrocarbon production at around 90 million barrels (bbl) equivalent and an average lifting cost of around US$10 US/bbl, the estimated OPEX due to corrosion threats in hydrocarbon production worldwide is around US$103 million dollars per day or over US$38 billion annually [2–4]. The contribution of corrosion threat to downhole operations is estimated at 1.6% of OPEX, making the overall downhole corrosion financial impact some US$5.3 billion annually. These figures, albeit an estimate and dependent on operator/

Table 1.1 Approximate economic impact of corrosion.[a]

OPEX		CAPEX	
11.5% Increase		8.5% Increase	
Activity	**Financial impact (¢/bbl)**	**Activity**	**Financial impact (¢/bbl)**
Downhole	1.6% Overall cost	Corrosion allowance	4
Maintenance	19.6	13%Cr for downhole	4.2
Shutdowns	1.2	Coatings	7.6
Support/inspection	7	Cathodic protection	3.2
Chemicals	5.2		
Major failures	6		
Personnel	0.02		

[a] Figures are based on year 2000 and have taken on board an annual inflation rate of 4–5%. They are approximate in cents/barrels and should be taken as purely indicative as they depend on application, location, operator, and logistics.
For the abbreviations, refer to the Appendix.

region/location, highlight the economic significance of corrosion and the vital role of mitigation, control, and prevention all requiring due and continuous attention. Based on the projection of figures from several publications and taking on board an average annual inflation rate of 4–5% since their publication, a breakdown of this figure as an indication of the economic impact can be summarised in Table 1.1 [2–4]. The increase in OPEX and CAPEX is due to the additional requirement for the implementation of corrosion mitigation measures when using CLAS as the base case. As an example, based on approximate figures in Table 1.1, for producing 90bbl/day, the overall annual cost of chemicals to mitigate corrosion is over US$1.7 billion.

1.3 Principal Types of Corrosion in Hydrocarbon Production

Many reviews and articles have focused on outlining the principal types of corrosion threat in hydrocarbon production systems with a view to channelling attention to key mitigation methods to minimise their occurrence. The reviews have demonstrated the significance of several types of metal-loss corrosion and cracking as the primary types of damage facing the industry [5, 6].

This section summarises the principal types of corrosion threat experienced in hydrocarbon production. This is as a precursor to the subsequent chapters that attempt to deal with individual subject areas in particular detail with respective mitigation methods. By no means does this section aim to describe different modes of corrosion threat as these are classical types and are shown and discussed in many publications.

The risk of internal or external corrosion becomes real once an aqueous phase is present and able to contact the pipe wall, providing a ready electrolyte for corrosion reactions to occur. The inherent corrosivity of this aqueous phase is then heavily dependent on the construction materials, the environmental conditions (temperature, pressure, presence of bacteria, etc.), and levels of dissolved corrosive species (acid gases, oxygen, organic acids, etc.) which may be present.

In hydrocarbon production, corrosion threats are mostly associated with the use of CLAS which continues to be the principal construction material. CLAS has been used extensively mainly due to its excellent properties, versatility, availability, and low cost. However, its inherent corrosion resistance in contact with production and water injection conditions is inadequate if not mitigated and this is the main source of the corrosion threats affecting the design and operation of production and water injection systems.

1.3.1 Corrosion Threats

As referred to earlier, given the conditions associated with oil and gas production and transportation and that of gas and water injection, corrosion must always be seen as a potential risk [7]. Therefore, the need to reliably handle wet hydrocarbons arises from the increasing number of fields where significant levels of CO_2 and H_2S are present under more arduous operating conditions. In addition, the need for increased production which invariably entails water or gas injection to maintain reservoir pressure or enhance sweep/capture of hydrocarbons (cf. recovery efficiency) can introduce O_2 and the potential for microbiological activity introduces further types of corrosion threat.

Extensive industry reviews have shown that corrosion in hydrocarbon production can manifest in several forms, all subject to the prevailing cathodic reaction, i.e. prevailing dissolved cathodic species (e.g. CO_2, H_2S, O_2) driving the overall corrosion reaction [5–8]. While most classical forms of corrosion are encountered in hydrocarbon production, the principal types where the majority of failures occur remain limited. The most prevalent types of damage encountered include metal-loss corrosion and localised corrosion manifested in the presence of CO_2 (sweet corrosion) and H_2S (sour corrosion), dissolved in the produced fluids and by the presence of dissolved oxygen in water-injection systems. These three types of corrosion threat are each addressed specifically in the present book due to their importance in terms of frequency of occurrence and the respective cost impact they impose on both CAPEX and OPEX [1–4].

This book deals primarily with aspects of internal corrosion, including microbiologically induced corrosion (MIC). However, as CUI continues to pose operational challenges in its detection and mitigation, Chapter 13 is allocated to addressing this type of external corrosion threat. Also Chapter 9 covers the challenges addressed by the coatings industry in controlling primarily external corrosion alone and in the presence of cathodic protection, where applicable.

Forms of corrosion of CLASs exposed to hydrocarbon production conditions are summarised schematically in Figure 1.2. Some of these are specific to an alloy/environment system and may not necessarily affect corrosion-resistant alloys (CRAs). The majority of these threat types are dealt with in separate chapters. It was not considered necessary to describe in classical detail each of the generic types of corrosion shown in Figure 1.2, as this is covered in most standard corrosion textbooks.

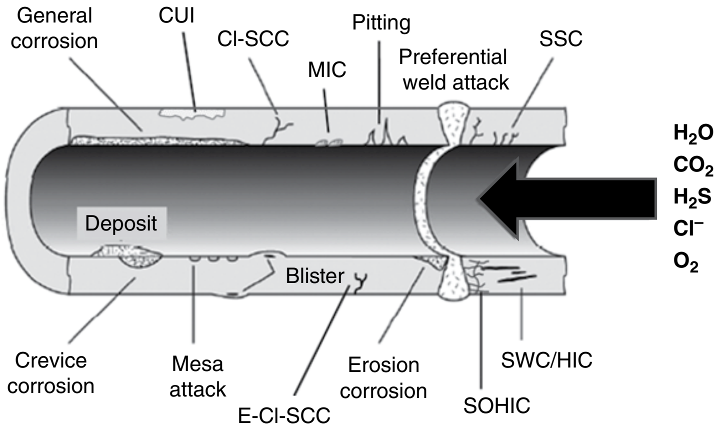

Figure 1.2 Principal types of corrosion threats on CLAS in hydrocarbon production.

1.4 The Way Ahead: Positive Corrosion

While the focus of this text is to describe practical measures to deal with corrosion in upstream operations, it is necessary to mention a few notes on the future role of the corrosion and materials discipline so that it can continue to successfully address corrosion threats.

It should be emphasised that the corrosion community has contributed enormously to the advances made in corrosion science, technology, and engineering which have subsequently led to step changes in material degradation mitigation practices [8]. The global awareness of the topic, including succinct communication, education, and public awareness, has come a long way over the past few decades. The impact of such measures has been felt across nations, governments, communities, and cultures. The corrosion profession across academe and industry, underpinned by professional bodies such as NACE International and the European Federation of Corrosion (EFC) and smaller national societies, continues to have substantial impact, with encouraging progress.

Corrosion remains a very interesting, challenging, exciting, rewarding, and relevant subject incorporating a diverse set of disciplines: Physics, Metallurgy, Chemistry, Engineering, and Art. Nevertheless the corrosion discipline is often in itself insufficiently always ready to intake and retain high calibre personnel. This is a critical loss to the industry and it is imperative that the anticipated shortfall is addressed effectively and sustainably. Furthermore, the discipline average age is increasing with the decreasing number of young engineers and scientists entering the community. According to NACE International, more than 60% of the members are aged above 40 and more than 40% aged above 50 years old. This deficit is believed to be correlated to the current niche image of corrosion within the professional society [8].

Reducing the number of dangerous events, injuries, and undesirable releases remains a top priority and the key focus of the profession's commitment to continually improving industrial and social safety standards. Corrosion societies across the globe have maintained a relentless effort to ensure that safety performances is improved through facilitating leadership, communication, education, and technology transfer. Looking to the future, the discipline will continue to be a key player in enabling the more efficient use of resources, thus reducing the impact on climate change. For example, the corrosion community has an instrumental role to play in the development and implementation of carbon capture, transportation, and storage technologies that can help reverse the effect of CO_2 emissions.

While the economic and HS&E impacts of corrosion and proactive prevention of corrosion-related failures are significant and major drivers, it still appears predominantly to be only the failures that make the headlines beyond the corrosion community, thus further underpinning a somewhat negative image of corrosion.

It is crucial to advance a different image of the corrosion community – a 'positive image' [8]. To underline what the corrosion community is capable of doing and has done in facilitating environmental benefits, help secure and facilitate wealth creation and the provision of societal well-being, safety and security. In sustaining the future of the community, it must attract a new generation of young enthusiastic engineers to the discipline, and it will be much more successful by presenting a positive vision rather than a 'life insurance' perspective.

1.5 Summary

- Corrosion failures account for 25% of all safety incidents, 2.8% turnover, 2.2% tangible asset, 8.5% increase on CAPEX, 5% of lost/deferred production, and 11.5% increase to the lifting costs, or more quantitatively between US$0.3–0.9/boe. OPEX uplift is governed by the operating regime and location, the maturity of the asset, and other parameters.
- Principal forms of corrosion threat in hydrocarbon production were outlined to include those in relation to the presence of H_2S and CO_2 in produced fluid and O_2 in injected fluids.
- The majority of corrosion threats in upstream oil and gas production are associated with metal loss CO_2 corrosion of CLASs (with implications for CAPEX and OPEX and HS&E) and are operator-dependent.
- The industry continues to lean heavily on the extended use of CLASs which are readily available and able to meet many of the mechanical, structural, fabrication, and cost requirements. Their technology is well developed and they represent for many applications an economic materials choice. However, a key obstacle – their Achilles' heel – to their effective use is their limited corrosion performance.
- This book provides an overview of the principal considerations and key issues associated with hydrocarbon production and transportation – a compendium of current best practices and state-of-the-art knowledge presented by expert and highly experienced field practitioners – to identify credible corrosion threats and their safe and cost-effective mitigation and proactive management. The content is meant to provide flexibility to be used in conjunction with competent technical judgements. Nevertheless, it remains the responsibility of the end user to judge its specific relevance and suitability for a particular application or context.
- Bearing in mind the influential role that the corrosion and materials discipline has played in providing improved safety and security, the community needs to be portrayed and championed in a positive way to attract a younger generation of high calibre individuals to further assist in the task of dealing with corrosion problems.