A PRACTICAL MODEL FOR MICROBIALLY INFLUENCED CORROSION RISK ASSESSMENT

by
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Abstract

Understanding what your risk is, what is driving your risk, and ensuring mitigative measures are effective are key to a strong risk-based inspection program. As a corrosion-resistant material, stainless steel is chosen for use in many applications. There is a wider understanding of degradation caused by microbiologically influenced corrosion. Leveraging microbially influenced corrosion of stainless steel and three major accidents involving corrosion, this work develops a model for corrosion risk assessments using bow tie analysis.

In the first part of this work corrosion of stainless steel is introduced. It reviews the various grades of stainless steel and why it is a corrosion-resistant alloy. It then reviews the status of research on its primary degradation mechanisms, pitting, and microbially influenced corrosion. This work then introduces inspection methods and techniques used to detect and monitor stainless steel corrosion to demonstrate the variation in results. The resulting variation impacts the fitness-for-service results and risk profile.

In the second part of the work, a model for corrosion risk assessment is developed based on three industrial accidents caused by corrosion. Monte Carlo simulations demonstrate the use of the corrosion risk assessment model and the resulting risk profile. The developed risk profiles are used to design corrosion intervention strategies that include corrosion prevention, to risk mitigation.

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Abbreviations

ALARP - is an acronym for As Low as Reasonably Practicable

BTA – Bow-tie analysis

BWE – Back wall echo

ETA – Event tree analysis

FFS – Fitness-for-service

FSH – Full-screen height

FTA – Fault tree analysis

KPI – Key performance indicator

MIC – Microbiologically influenced corrosion

NDE – Non-destructive Examination

NDT – Non-destructive Testing

POD – Probability of Detection

1 Introduction: Corrosion Risk Assessment

Plants have competing priorities for their maintenance and operations budgets to balance asset life and revenue. Stakeholders challenge line items in budgets to ensure that expenditures identify and manage operational risks to ensure budgets are used in the best interest of overall asset life and revenue. One of these expenditures that needs to be balanced is the integrity program.

Integrity programs govern maintenance and inspection activities for an operation. One aspect that falls under this program is corrosion. Corrosion is a significant issue in most industries, with an estimated global cost of US$ 2.5 trillion and the use of current corrosion practices could result in savings of up to 35% of the cost of corrosion (Bowman et al., 2016). The use of stainless steel is one mitigation strategy used by engineers in many industries as one of their tools to mitigate corrosion life cycle costs (Koch et al., 2002). While stainless steel can reduce the occurrence of corrosion under some conditions, corrosion is still an issue. Microbially influenced corrosion (MIC) is one type of corrosion that can degrade stainless steel and can impact the integrity of the asset. Understanding how forms of corrosion such as MIC can impact the safe operations of stainless steel assets is required to reduce corrosion-related failures.

The use of stainless steel is increasing, driven by demand from the infrastructure, energy, food and beverage, and resource sectors (Grandview Research, 2023)(Nickel Institute, 2021). Part of this demand is that stainless steel may reduce the life cycle costs caused by corrosion (Abdel_Ghany et al., 2022; Clayton et al., 2004; Naghizadeh et al., 2022).

Although stainless steel is a corrosion resistant alloy (CRA), it still can be degraded by various corrosion methods. Two of its potential corrosion mechanisms, pitting and microbiologically influenced corrosion (MIC), can have significant corrosion rates (Outokumpu, 2017). Given that austenitic stainless steels are a prevalent form of stainless steel and that MIC accounts for approximately 10% to 20% of corrosion costs (Hashemi et al., 2018), austenitic stainless steels and MIC were chosen for this work.

The Association for Materials Protection and Performance (AMPP), formerly NACE, defines microbiologically influenced corrosion as "corrosion affected by the presence or activity, or both, of micro-organisms. The micro-organisms that are responsible for MIC are typically found in biofilms on the surface of the corroding material. Many materials, including most metals and some nonmetals, can be degraded in this manner"(NACE International, 2018). A report published by NACE in 2016 estimates the global cost of corrosion at 2.5 trillion US dollars. This form of degradation impacts diverse structures including screws, sprinkler systems, bridges, and nuclear power plants. Failure to identify, diagnose and action MIC has led to premature failures, premature replacement, loss of containment, and process shutdowns (Olszewski, 2007)(Eckert & Skovhus, 2021). Some notable examples are the BP pipelines in Prudhoe Bay, Alaska, and well casing in Aliso Canyon California. In Alberta, Canada, publicly available data on oil and gas pipelines indicate that 13.6% of internal corrosion incidents and 4.8% of external corrosion incidents are MIC-related (Eckert & Skovhus, 2021).

MIC can be either a chemically mediated process or electrically mediated processes that generally presents as localized corrosion. MIC corrosion rates are a function of the types of bacteria and their environment which presents a challenge for researchers to model as research typically focuses on one type of MIC (Rao & Mulky, 2023). The result is that there are no accurate models to predict MIC and its growth. Early detection, mitigation, or elimination is key to limiting the damage caused by MIC. Such early detection must have suitable surveillance to ensure the timely identification of issues. Surveillance must be supported by a robust inspection program that appropriately selects the inspection location(s), inspection method(s), and the appropriate inspection technique(s). While inspection itself does not directly reduce the probability or consequence of MIC, the knowledge gained can facilitate early detection of potential issues. The challenge is that recent papers by researchers (Bonifay et al., 2017; Eckert et al., 2021; Eckert & Skovhus, 2019; Skovhus & Eckert, 2014), have demonstrated that risk-based inspection (RBI) programs do not address the potential severity of MIC.

Once an issue is detected, an understanding of the probability of failure can influence the actions needed to mitigate potential consequences and costs. Understanding the capabilities of inspection methods and techniques to detect MIC provides one element in evaluating the probability of failure (Health & Safety Executive, 2013). This evaluation also involves understanding if the equipment is still fit for purpose. In the case of pressure equipment, API 579-1/ASME FFS-1 Fitness-For-Service Evaluation is used to analyze, evaluate, and monitor equipment for continued operation (ASME, 2023). This recommended practice outlines the protocols that assess equipment's continued fitness-for-service (FFS). Which in turn facilitates the safe and reliable operation of pressurized equipment used in industrial facilities (Inspectioneering , 2023).

Inspection and integrity programs are used to monitor, report, and remediate degradation to prevent loss of containment. For most industries the ability to articulate the level of risk to a production or operating facility caused by corrosion presents challenges. There are typically multiple, competing priorities for maintenance and repair activities and resources. Thus, there is a need to clearly understand and be able to demonstrate the risk(s) associated with degradation. This ensures that the resources are appropriately allocated for repair or monitoring.

While there are existing risk assessment tools for corrosion, they typically are complicated, focus on one corrosion mechanism, or are based on the general corrosion of carbon steels. Stainless steel and/or MIC specific risk assessment tools require data that may not be available and generally do not provide support for the improvement of the overall integrity management system. To develop a model that integrates stainless steel and corrosion mechanisms, like MIC, an investigation into how stainless steel and MIC present to an integrity team is needed. This study is broken down into three sections. The first section introduces stainless steels, and then focuses on austenitic stainless steel, their properties, and two of the most prevalent forms of corrosion associated with this material. The intent of this section is to demonstrate the complexity and challenges associated with the degradation of austenitic stainless steel. It also demonstrates the integrity tools used to monitor degradation and their impact on the risk profile of an asset.

The second section of this study explores the nature of risk associated with corrosion related degradation. Leveraging three case studies the author develops a model to evaluate the risk associated with corrosion by using a bow tie approach. This section highlights the effect of various integrity monitoring tools identified in the first section on the resulting risks.

In the final section, the author presents how the corrosion risk assessment model can be incorporated into existing risk-based inspection or assessment programs to communicate the risk of degradation to stakeholders.

2 Degradation of Austenitic Stainless Steels

2.1 Introduction

The use of stainless steel is steadily increasing in a variety of sectors given its mechanical properties and corrosion resistance. A recent report by Grand View Research has indicated that the use of stainless steel is increasing. This same report has highlighted that currently, 54% of the stainless-steel market is austenitic stainless steel (Grand View Research, 2023). Stainless steels, like all materials, are susceptible to degradation. However, in many cases, industry presumes the use of corrosion resistant alloys will not degrade. There are multiple degradation mechanisms that are applicable. The two degradation, and potential failure, mechanisms are pitting and MIC. In addition to being difficult to detect it is also difficult to distinguish between the two mechanisms.

Identifying that MIC (as opposed to another type of localized corrosion) is the degradation mechanism at work requires an understanding of three ingredients: the presence of micro-organisms, chemical changes caused by the micro-organisms, and physical degradation of the materials (Bowman et al., 2016; Linhardt, 2010; Little et al., 2006). Unfortunately, in older assets or industries with less mature asset integrity systems, the ability to monitor and trend all three ingredients may present challenges due to cost and level of corrosion knowledge. Corrosion coupons, chemical sampling, and inspection data all need to be aligned and trended to identify and monitor MIC. Frequently, operations teams rely only on inspection and chemical management by subcontracted companies to monitor/prevent MIC. When this service is isolated, it limits the effectiveness of the program and minimizes its value.

Detection of MIC may be either online or offline. Online detection removes samples of biomaterials from the system in question using sample bottles, coupons, or some combination thereof. Offline detection requires the removal of a sample of the material section followed by detailed laboratory testing. Regardless of the method, both require a combination of tools including corrosion coupons, biofilm detection, process monitoring, and chemical sampling (Eckert & Skovhus, 2019; Jensen et al., 2013; Skovhus et al., 2017a). Support from laboratory activities to characterize surface characteristics, micro-organism populations, and any corrosion byproducts is also needed (Kannan et al., 2018).

Failure analysis with destructive tests provides excellent insight into MIC processes. Testing the corroded sections may not provide accurate details on MIC progression or the corrosion rate. It only provides information about its current state. This is problematic as the rate of change information is needed to prioritize repairs and monitor the effectiveness of mitigative strategies such as pigging or biocide programs. This approach damages or destroys the equipment. Replacement of removed sections requires additional resources and increases the overall cost. The result is that this approach is likely prohibitively expensive for an operating facility.

The intent of the literature review will focus on austenitic stainless steel as they are the predominant form of stainless steel used in industry. It will highlight the challenges associated with the degradation of stainless steel.

A review of MIC mechanisms associated with austenitic stainless steels aims to determine the current state of knowledge of the impact of MIC on austenitic stainless steel, to determine if traditional inspection techniques to monitor MIC are acceptable, and to assess whether the information provided by these techniques affects the understanding of the risks caused by the degradation.

2.2 An Overview of Stainless Steels

To improve the corrosion and oxidation resistance of low-carbon steel, chromium was added as an alloying element resulting in stainless steel. The chromium reacts with an oxidizing agent and forms a thick, tightly adherent layer of oxide (Cr_2O_3). This film protects the underlying metal by acting as a barrier to corrosion. To be considered a stainless steel there must be at least 12% Cr. Additions of nickel improve the corrosion resistance in neutral or weakly oxidizing environments (Heidersbach, 2018; Nickel Institute, 2021; Sun et al., 2022).

2.2.1 Classes of Stainless Steels

There are typically five classes or categories of stainless steel. They are classified based on their crystal structures that generate their composition and mechanical properties. The categories are:

- Martensitic
- Precipitation hardened
- Ferritic
- Duplex
- Austenitic

2.2.1.1 Martensitic

Martensitic stainless steels are an alloy of Fe-C-Cr that is heat treatable and magnetic due to its body centre cubic (BCC) structure. They contain 12 – 17% Cr with 0.1 to 1.0% C to allow the formation of a martensitic structure. This improves their strength and hardenability relative to other forms of stainless steel (Outokumpu, 2017). This form of stainless steel is used when corrosion and oxidation resistance is needed with higher strengths or creep resistance at higher temperatures (W. M. Garrison & Amuda, 2017). The mechanical properties and toughness properties are controlled through heat treatment. The corrosion properties of martensitic stainless steels are lower than those of austenitic and ferritic stainless steels. This is a function of the lower Cr content which is kept to 12%. The addition of more Cr promotes ferrite formation instead of austenite. Austenite is needed to allow the formation of a martensitic structure. Martensitic stainless steels are susceptible to atmospheric corrosion.

2.2.1.2 Precipitation Hardened Stainless Steels

Precipitation hardened stainless steels are an alloy of Fe-Cr-Ni that can be hardened by solution treatment and subsequent aging. This form of stainless steel has less Ni content than austenitic stainless steel. It is relatively ductile, has high strength, and maintains good corrosion resistance. The two common forms of precipitation hardened stainless steels are semi-austenitic and martensitic.

2.2.1.3 Ferritic Stainless Steels

An alloy of Fe-Cr with a BCC structure that contains 12 – 30% Cr. It has lower strengths compared to martensitic stainless steel. It is typically used where corrosion resistance of Ni-containing stainless steels is needed, and the cost is a concern. Ferritic stainless steels typically have lower ductility, high notch sensitivity, and lower weldability. Corrosion resistance is affected by its chemistry. It has lower pitting resistance compared to austenitic stainless steel. Ferritic stainless steels are susceptible to intergranular corrosion, particularly if chrome carbides and nitrides are precipitated at grain boundaries. Precipitation of carbides and nitrides locally decreases the chrome content below 12%.

2.2.1.4 Duplex Stainless Steels

Duplex stainless steels are a two-phase alloy of Fe-Cr-Ni-Mo typically with equal amounts of ferrite and austenite phases. The Cr content is typically between 20-30 wt% with 5 – 8 wt% Ni. Comparatively, the dual phases provide better strength and stress corrosion cracking resistance to other stainless steels. The corrosion properties are like those of austenitic stainless steel.

2.2.1.5 Austenitic Stainless Steels

Austenitic stainless steels are a Fe-Cr-Ni alloy with a face-centred cubic structure. Relative to duplex stainless steel, this type of stainless steel has less chromium, less molybdenum, and more nickel. The nickel stabilizes the formation of austenite. In the annealed condition this stainless steel is non-magnetic. This form of stainless steel is one of the most common types, due to its excellent low temperature toughness, weldability, and corrosion resistance.

2.2.2 Pitting Corrosion of Austenitic Stainless Steels

From a corrosion perspective, stainless steels perform better relative to carbon steel. At lower temperatures, this is a function of the performance of a passive layer on the metal surface. The continuity, and coherence of the passive film are a function of the environment and composition of stainless steel and result in the low corrosion rates associated with stainless steel (Cramer & Covino, 2005).

2.2.2.1 Passivation Layer

Stainless steels, unlike carbon steels, form a protective film known as a passivation layer. Although generally modelled as a homogeneous, uniform oxide or hydroxide film it is a multilayered structure. The inner layers are typically oxides, and the outer layers are hydroxide (Marcus et al., 2008; Strehblow, 2016). In the case of austenitic stainless steel, the passivation layers are a protective CrO film. This film provides a barrier to corrosion. The passive film forms in the presence of oxygen. The level of stainless steel passivity is impacted by the type and service environment of the stainless steel (Grubb et al., 2018). To provide an estimate of a stainless steel's resistance to pitting, an empirical relationship between the critical pitting temperature (CPT) and primary alloying elements (Cr and Mo) was determined by Lorentz. This relationship is known as the pitting resistance equivalent number (PREN) (Jargelius-Pettersson, 1998). This allows the general comparison of the corrosion resistance of stainless steel. Larger values of PREN typically have better corrosion resistance. The numerical value of the PREN is approximately equal to the critical crevice temperature (Celsius) in natural seawater or in ferric chloride solutions (Heidersbach, 2018; Revie, 2011).

Pitting corrosion occurs when a localized attack produces cavities in the material. Pitting will typically undercut the surface of the material where the anodic area is small relative to the cathode. The localized nature of the attack and the surface size of the cavities make pitting corrosion difficult to detect and predict. The resulting corrosion products, known as tubercles, can obscure the identification of the pit and its progression until such time there is a perforation.

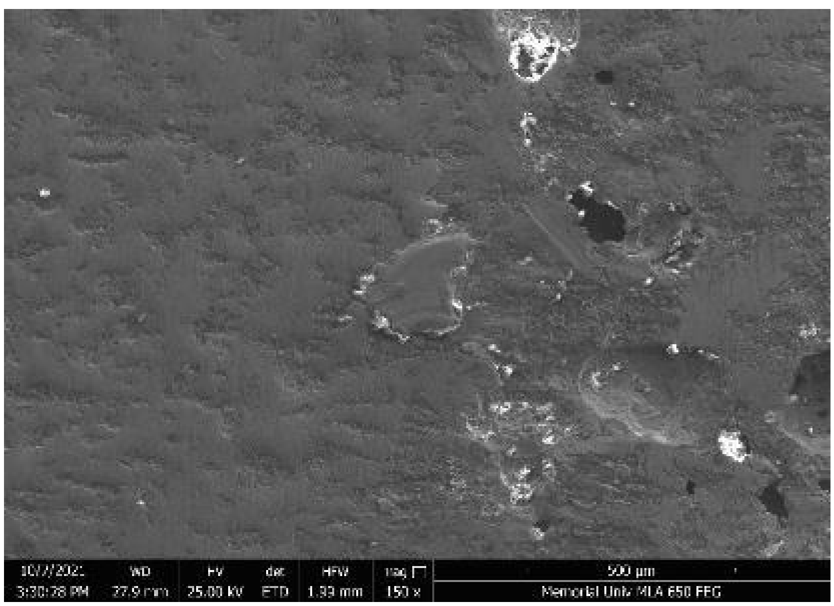

Figure 1 A SEM image of the inside surface of pressure vessel that has been degraded by MIC. Note the pit cover in the centre of the image.

Tubercles are porous with scale deposits that can impede biocides and corrosion inhibitors that minimize corrosion activity.

Uhlig's Corrosion Handbook (Revie, 2011) divides pitting corrosion into initiation and growth steps. Generally, the metallurgy of austenitic stainless steels, particularly 316L, is resistant to pitting due to its self-healing passivation layer. The effectiveness of the passivation layer can be improved by pickling and passivating the stainless steel (Revie, 2011). Pickling involves using an acid to remove a thin layer of material. The acid removes any oxide scale and chrome depleted areas created during fabrication. Passivation uses an oxidizing acid to help restore and improve the passivation layer (Crookes, 2007). Passivating stainless steel is quite helpful in resisting pitting caused by MIC (Allé, 2003). Pickling and passivation involve the removal of surface contaminants and improve the formation of the passive layer.

After pit initiation, the growth of the pit is in the form of a metastable pit. In conventional pitting, this is diffusion-controlled; and requires an effective barrier for diffusion. As a pit grows a thin cap is generated and typically serves as a barrier. If lost, it may allow the pit to re-passivate. As the metastable pit grows, there is active metal dissolution which creates a cave. The growth of the cave is predicated on electrochemical drivers and the metallurgy of the cave.

Once the metastable pit has grown to sufficient depth, it becomes self-sustaining. Its rate of growth is controlled based on diffusion (Burstein et al., 1993). In pitting corrosion, variations in the electrochemical cell within the pit drive its morphology. The pit's depth from pitting corrosion is governed by the kinetics of diffusion, whereas the conductivity drives its width within the pit solution. The overall growth of the pit results in a hemispherical shape under its cover (Ghahari et al., 2015).

2.2.3 MIC of Austenitic Stainless Steels and How it Progresses

2.2.3.1 Forms of MIC and their effects on Stainless Steel

While there are various theories about the kinetics and behavior of MIC, they align in that it is an electrochemical process where microorganisms have a positive or negative effect on the corrosion rate (Skovhus et al., 2017b). They are also generally aligned in that the micro-organisms can influence the creation of the ingredients needed for a corrosion cell, namely the anode, cathode, electrical connection, and electrolyte.

2.2.3.2 Planktonic bacteria

Planktonic bacteria in a system become sessile attach themselves to the metal surface and generate layers of protective substances, thus creating a biofilm on the surface. Upon reaching a critical thickness of biofilm, the electrochemical environment below the biofilm becomes significantly different from the bulk solution in this system. The value of critical biofilm thickness has yet to be clearly defined and is one of the issues adding to the complexity of understanding MIC behaviour and impact. The micro-environment below the biofilm facilitates the creation of a corrosion cell (Javaherdashti, 2017).

Fluid flow in the system provides oxygen allowing stainless steel substrates to maintain passivation. In a low-flow or stagnant environment, biofilms form. The nature of the individual biofilm drives the behaviour that creates the associated micro-environment (Beech, Iwona B. and Gaylarde, 1999). The result is a microbiologic and electrochemical challenge. Research by Xu, Blackwood, Beech, and Gu has shown that it is likely that flora of bacterium may be found in biofilms (Bonifay et al., 2017; Little, Hinks, et al., 2020; D. Xu & Gu, 2011). While the electrochemistry aspects seem well understood, the microbiological mechanisms need more investigation (D. Xu et al., 2016). Some of the MIC groups associated with stainless steels include sulphate-reducing bacteria (SRB), manganese-oxidizing micro-organisms (MoMo), and acid-producing bacteria (APB).

2.2.3.3 Sulfate-reducing Bacteria

Sulphate-reducing bacteria (SRB) are anaerobic. Thus, SRBs do not require oxygen for growth and activity. SRBs have been found to create galvanic couples that reduce ferric ions (Kannan et al., 2018). They typically rely on organic nutrients for their carbon source to support cellular metabolism. However, when organic nutrients are not available, they switch to iron oxidation (Gu, 2014). The bacteria that reduce sulphur compounds are one of the most prevalent forms of MIC (Javaherdashti, 2017; Jogdeo et al., 2017; Little, Blackwood, et al., 2020).

SRBs are one of the most studied forms of MIC. In experiments with AISI 304 stainless steel, researchers observed that SRBs produce hemispherical pits with rough black interiors (Werner et al., 1998; XU et al., 2006).

Some of the corrosion byproducts resulting from the interaction of SRBs and austenitic stainless steels include hydrogen sulfide and chrome sulfide which are a function of Cr_2O_3 reacting with biogenic H_2S (Duan et al., 2006). The resulting corrosion caused by the rod-shaped SRB results in oblong pits with black tubercles (XU et al., 2006).

2.2.3.4 Acid Producing Bacteria

Acid Producing Bacteria (APB) produce acid as a function of their metabolic processes, resulting in the illusion that the bacteria "eat" the metal (Beech, Iwona B. and Gaylarde, 1999; Gu & Galicia, 2012; Inaba et al., 2019). In this MIC form, the bacteria's cells produce their electron acceptor derived from organic carbon. The organic acid results in a low pH below the biofilm (Guan et al., 2014). In some cases, the bacteria will also produce their own acid when starved (Blackwood, 2021). The resulting acids react with ferrous irons resulting in brown, dense, brittle deposits of FeCO3 and chrome oxides. Both pitting and cracking have been seen under SEM (Chamritski et al., 2004b; Starosvetsky et al., 2008).

2.2.3.5 Iron-Oxidizing Bacteria

Iron oxidizing bacteria (IOB) are bacteria that use iron as their source of energy (i.e. IOB oxidize iron) and have been found to be one of the initial bacteria colonizers on steel infrastructure (Emerson et al., 2010). IOB typically present as a red-brown deposit (Chamritski et al., 2004b) and results in a corrosion mechanism that isn't unlike crevice corrosion. Current research has shown that IOB can have either positive or negative impacts on MIC corrosion rates (C. E. Garrison et al., 2019).

2.2.3.6 Manganese-Oxidizing Bacteria or Micro-Organisms

Manganese-oxidizing bacteria (MoMo) oxidize the manganese from the surrounding fluid flow, increasing cathodic polarization at the metal surface. This form of MIC seems relatively well understood. The schematic showing this form of MIC is illustrated in **Error! Reference source not found.**.

MoMo produces MnO_2 that increases the cathodic reaction with a minimal fluid flow that will provide additional aeration and nutrients to the biofilm, reducing the available oxygen adjacent to and below the biofilm. The result is a weakened passivation layer on the stainless steel, and a strong cathode, making the stainless steel more anodic. Presuming the biofilm maintains a current of +150 $mV_{SCE,}$ the stainless steel will not repassivate (Linhardt, 2006a).

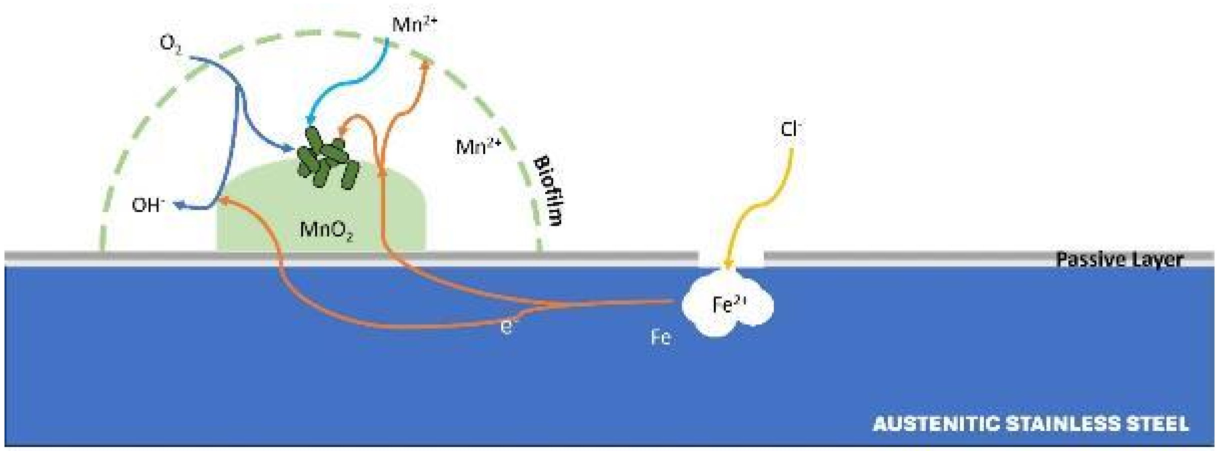

Figure 2 A schematic of manganese-oxidizing micro-organisms, adapted from (Linhardt P. , 2001)

Thierry et al. have evaluated the effects of temperature, chlorine, and oxygen content on the corrosion potentials of MoMo. They have concluded that at seawater temperatures between 5° and 37°C cathodic currents promote biocorrosion. They also showed that the oxygen content of 6 ppm resulted in the ennoblement. As dissolved oxygen content increased, so did the reduction current of oxygen, meaning that there will be a corresponding increase in localized corrosion rate (Thierry et al., 2015). Furthermore, there are indications that even in water with minimal dissolved manganese or chlorides, MoMo can still produce MnO_2 (Allé, 2003).

The overall result of the micro-organisms is a shift in the electrochemical potential under the biofilm, negatively impacting the passivation layer. With the material's protective layer degraded, pits can initiate. The pit then nucleates, forming a cave containing an acidic solution. The biofilm and resulting tubercle can then occlude the pit allowing its growth until the kinetics for corrosion are no longer present (Frankel, 2003; Linhardt, 2006b).

Each form of MIC may degrade the corrosion resistance of stainless steel as each bacteria type may increase the cathodic reaction rate. The increased cathodic rate means the anodic reaction rate must increase, creating the resulting corrosion rate.

2.3 Pitting Vs MIC?

There has been little difference observed in the morphology of pits caused by MIC compared to those initiated by chloride or sulphide attack in various studies (Zhang et al., 2007) (Geiser et al., 2002) (Szklarska-Smialowska, 2005)(Chung & Thomas, 1999). This anecdotal observation is reinforced by Geiser et al (Geiser et al., 2002) and Zhang et al.(Zhang et al., 2007). In their experimentation, they found that initially there were many small pits found in the presence of bacteria and that post-initiation, MIC morphology, and pitting corrosion appear to be indistinguishable.

Through experiments by Zhang, Geiser, and Chung and their observations related to MIC pit morphology and progression:

- Morphology of the pitting initiated by MIC reflected the overall shape of the bacteria colony.
- IOBs generate wide and shallow pits.
- SRBs generate large and deep pits.
- SRB & IOB generate larger and deeper pits, some with cracks; and,
- Chloride concentration deepens pits.

2.4 MIC and the Implications to Corrosion Rate

For pressure equipment, pitting and/or MIC can result in loss of containment with a relatively small percentage of weight loss in the section. As such, localized corrosion like pitting and/or MIC is a major concern (Caines et al., 2013; Li et al., 2011). The small section loss means that understanding the size and distribution of pitting is critical for fitness-for-service.

Corrosion rates vary with bacterium types, material microstructures, and the effectiveness of the stainless-steel passivation layer effect (Chamritski et al., 2004a; Dong et al., 2021; Puentes-Cala et al., 2022; C. Xu et al., 2008). Additionally, there are still concerns related to the biological mechanisms and their influence on corrosion rates (Gu, 2014; Little, Hinks, et al., 2020). Research has also demonstrated that the pit depth of MIC is far greater than a uniform corrosion rate (Javed et al., 2017). This ignores that in some cases MIC-initiated pitting can re-passivate (Linhardt, 2006b). As such conventional use of corrosion rates to determine the resulting probability of failure for a risk assessment would be ineffective as a change in one of the variables could easily impact the basis used to determine the probability of failure. The impact is that there is a need to monitor the progression of MIC in the field.

Empirically, corrosion rates attributed to MIC are higher than conventional pitting. There also can be variations in corrosion rates within the same system (Skovhus et al., 2014). It has been previously determined that corrosion rate is a function of kinetics and mass transfer (D. Xu et al., 2016). More recently, it has been experimentally found that the MIC corrosion rate varies with different voltages and currents (Dong et al., 2021).

Several pitting and corrosion rate models have been developed and were reviewed by Marciales (Marciales et al., 2019). This review along with a subsequent review by Khan et al. to create a probabilistic model are predicated on one or two forms of MIC, typically SRB and APB (Dawuda et al., 2021). These mechanistic models consider both the chemical and microbial mechanisms of MIC. However, they do not consider the additional critical factors such as microbial growth and interaction or the resulting chemical reactions. Furthermore, none have been validated by any field trials.

2.5 Discussion

Most MIC activity results in a pitted stainless steel. A pitted surface facilitates the formation and growth of biofilm causing MIC. Thus, the progression of MIC can be mistaken or confused with pits initially caused by other mechanisms. The variation in corrosion rates among researchers and those found in industry is quite large. This suggests that the corrosion rate due to the MIC of stainless steel is a function of multiple microbial types and varies with the type of bacteria involved. The types and quantities of the bacteria flora within the system drive the rate of corrosion found in carbon steel (Bonifay et al., 2017).

Current research and empirical evidence indicate that there is no way to distinguish between MIC and pitting in austenitic stainless steels, rather that MIC and/or pit morphology are indistinguishable without sampling of the biofilms and pit chemistry. Moreover, it is likely that MIC and pitting corrosion are complimentary and can impede the repassivation of the material surface both inside and outside of the pit. While surface morphology may be ambiguous in determining the driving degradation mechanism, the ability to monitor the change in pit morphology is critical to monitoring the probability of failure resulting from pitting and/or MIC behaviour.

Pitting corrosion and MIC initiate at a microscopic level and are a function of surface metallurgy and geometry. Based on the mechanistic models the cocktail of pitting corrosion and MIC likely generates pits whose depth follows a power law. As such, the ability to monitor pitting corrosion and MIC pit growth is important. Failure to monitor the resulting pitting may have catastrophic effects.

Modelling of MIC is progressing; however, it isn't robust enough to predict corrosion rates. Though the models are improving our understanding of the degradation processes it is still stochastic. Current risk assessment processes are based on current corrosion management philosophies and incomplete MIC models. As such the tools and processes currently in place may not fully define the associated MIC risks since assumptions are made about the detection and progression of MIC. Most notably, microbial surveillance, inspection, and biocide programs will effectively detect and mitigate the risks caused by MIC.

Thus, there is a need to validate research and the resulting modelling against empirical data from various industries. Combining these data sets with inspection data will facilitate early detection, and mitigation and enhance risk-based assessments and/or the continued fitness-for-service of the system. Alternatively, the rate of pitting corrosion will result in rapid degradation, relative to the general corrosion of stainless steel, increasing the probability of failure. Regardless, if perforation results in a low or high consequence, the higher probability generates a higher risk. Using MIC as an example, it appears that simply addressing symptoms of degradation may not result in a long-term or cost-effective solution(s). It may simply defer a larger problem until later in the lifecycle of the asset(s).

This work intends to develop a model for corrosion risk assessment that is based on the degradation of austenitic stainless steels by microbiologically influenced corrosion.

2.6 Fitness for Service/Purpose

Some level of biofilm and bacteria will likely be present in many processes. Consequently, the ability to fully eliminate MIC from stainless steel systems, particularly when it is not fully understood, is minimal. As such, owners/operators of plants must have an integrity management tool and system in place to define why/how a system is or is not fit for its purpose.

Part of an integrity management system involves defining an equipment assessment strategy. To support the strategy owners or operators collect data for comparison against engineering design data, corrosion rate expectations, and the desired asset life (Nettikaden et al., 2014). Maintenance strategies are a key part of the integrity management strategy and are implemented into operational processes and monitored against the intended operating windows. Inspection activities are another aspect of integrity management. These activities are used to monitor equipment for issues that impact their operations.

When the inspection findings identify a gap between the design/operating requirements and the asset life there are four options for the owner/operator: repair, re-rate, replace, or run (continue to operate). The option selected for safe operation must be based on an engineering and business evaluation that confirms the integrity of the equipment in its intended operating window. This fitness-for-service (FFS) evaluation is critical for stakeholders. In the 1990s a joint industry project was led by the Materials Property Council to develop an industry guideline to standardize the fitness-for-service of refining equipment (Anderson, 1995). In 2000, the American Petroleum Institute (API) published a recommended practice that outlined FFS procedures for industry and regulators in managing pressure equipment throughout its lifecycle (Buchheim, 2001). The recommended practice was adopted by ASME in 2007. The standard is now known as API 579/ASME FFS-1, ‘Fitness-for-service’, and has been widely used outside of the refining industry (Anderson, 2007). This standard takes a multidisciplinary approach to evaluate the fitness-for-service (FFS) of damaged and/or degraded equipment to support decision-making.

Fitness-for-service per API 579 has three levels of assessment based on the driving degradation mechanisms, level 1, level 2, and level 3. Level 1 FFS has the most conservatism, allowing more variation and a basic level of knowledge to complete relative to level 2 and 3 FFS. Level 3 FFS has minimal conservatism, and requires significant levels of detail, robust inspection data, and a detailed understanding of engineering. The result is that:

- Level 1 – Involves basic calculation using standardized formulae in API 579.
- Level 2 – Involves more in-depth calculations and engineering analysis.
- Level 3 - Requires advanced engineering tools such as finite element analysis, computational fluid dynamics or other modeling tools.

If an FFS performed in accordance with API 579 fails level 1, level 2 is attempted. If equipment fails a level 2 FFS it progresses to a level 3 FFS. If the equipment fails a level 3, then new, suitable safe operating conditions can be identified, the equipment can be repaired or decommissioned. Regardless to which level of FFS the equipment is successfully completed the status and remaining life is calculated.

There is detailed guidance in API 579, particularly in Part 6 on how to perform FFS, and notably for degradation due to corrosion. API 579 addresses local thin areas like pitting. These points form the foundation of the FFS assessment. If pitting is involved then the equipment should not be operated within its creep range, which is defined in the recommended practice. Detection of pitting uses a local thin area (LTA) in its evaluation. Future corrosion allowance is based on the projected metal loss for the region. As such, the data required needs to select a population of pits that represent the damage. More importantly, the inspection techniques that are used to characterize the opposite surface must not overlook significant damage (ASME, 2016).

2.6.1 Requirements for Pitting Damage Assessment per API 579

API 579 is the only major FFS code to address pitting damage as part of its methodology (Shekari et al., 2015). Pitting corrosion damage is captured in part 6 of API 579 and the methodology is based on four types of pitting damage. These are:

1. Widely scattered pitting that occurs over a significant region of the component.
2. A local thin area (LTA) located in a region of widely scattered pitting.
3. Localized regions of pitting, and
4. Pitting confined within a region of an LTA.

For the level 1 FFS assessment the pitted area and maximum pit depth of the component are compared to the pit charts found in the code. This is then used to calculate the remaining stress factor (RSF). For the level 2 assessment, a pit-couple is used as the measure of damage. The code evaluates the metal loss of two pits and the distance between them. This representative pit-couple is used to calculate the RSF.

API 579 recognizes that accurately measuring pitting is a challenge and provides several recommendations. These are summarized below:

1. Pitted surfaces may need to be cleaned to remove dirt, scale, or damaged coating.
2. Pit gauges and rulers or callipers should be used to measure the depth and distance between pits.

3. It is difficult to measure small-diameter pits using ultrasonic techniques. Radiographic techniques can be used.
4. Inspection techniques that characterize pitting from the opposite surface should only be used when there is sufficient resolution.
5. If the material could be susceptible to brittle fracture supplemental inspection per other sections of the code is required.

The previous literature review highlighted the stochastic nature of MIC and pitting of stainless steels. It also found that mechanistic models while insightful do not fully model the behaviour (Marciales et al., 2019). This implies that the assumptions used by API 579 as it relates to pitting, particularly if caused by MIC may be oversimplified. It also suggests that inspection techniques used for locating and sizing MIC pitting must be as accurate as possible. The code does not specify what it means by "sufficient resolution". This suggests that so long as the significant damage is not overlooked then UT can be used from the opposite side surface. Guidance is given on the number of readings and grid sizes; however, details on the UT technique and procedure are left to others (ASME, 2016; Young, 2019). The implications of this will be shown in the section 3 of this work.

2.7 MIC Detection, Sizing, and Monitoring via Inspection

MIC and pitting corrosion have physical and chemical markers. Chemical sampling programs may see markers of corrosion. Since they are not linked to process chemistry and process conditions they cannot qualitatively or quantitatively determine the amount or rate of degradation (Cox, 2014).

API Recommended Practice 571 suggests that the inspection and monitoring of MIC is performed by microbial monitoring using non-DNA and DNA-based methods. It also recommends using chemical surveillance tools like measuring residual biocide, visual appearance, and smell (American Petroleum Institute, 2020).

In industry, microbial monitoring includes non-DNA and DNA-based testing. Non-DNA testing involves tools such as serial dilution testing, microscopy, and ATP testing. DNA-based testing involves genomic testing like qPCR testing. Microbial monitoring requires physical samples that must be taken in affected and unaffected areas. Chemical and microbiological surveillance is critical to the detection and mitigation of MIC (Eckert & Skovhus, 2021; Skovhus et al., 2017a).

A detailed review and comparison of the chemical and microbiological methods, including sample collection, is beyond the scope of this work. For the purposes of this work, we have intentionally focused on NDT it would be used to measure damage caused by MIC.

To determine whether the equipment is still serviceable for the asset lifecycle or if mitigation methods are effective, we must understand the amount of degradation and progression rate. The amount of degradation allows the owner or operator to evaluate the effectiveness of risk mitigations. (Eckert & Skovhus, 2014) While chemical and microbial surveillance provides good information, multiple methods of information are needed to evaluate MIC or abiotic corrosion (Eckert & Skovhus, 2019).

There is anecdotal industry experience that MIC pitting of stainless can be difficult to detect visually and requires additional surface NDT to observe pitting. This anecdotal experience is supported by findings from the Programme for the Inspection of Steel Components (PISC II) study (Crutzen et al., 1994). This is likely a function of the small surface indications caused by the pit cover, that corrosion damage may be larger sub-surface as shown in Figure 3. The result is that the small openings associated with MIC or fine pitting do not contrast enough with surrounding features and are either missed visually or attributed to the equipment manufacturing or in-service conditions.

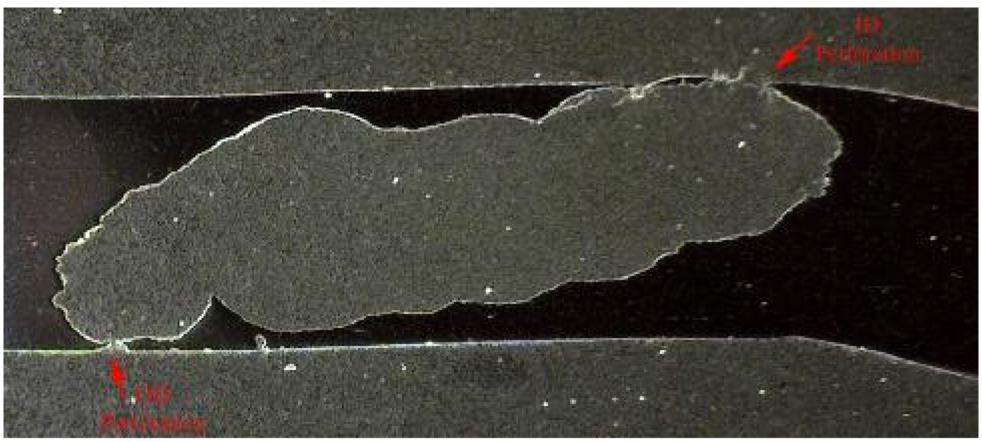

Figure 3 A cross-section of MIC damage to a 1.8mm thick pipe. Note that sub-surface corrosion is significantly larger than the ID or OD perforation.

Understanding the impact of microbial activity and its effects on pit morphology will help identify, categorize, and prevent MIC-generated risks. In a recent publication by Texas A&M University, they reviewed numerous new detection methods, including electrochemical noise, open circuit potential, LPR, etc. (Kannan et al., 2018). The authors highlighted that the tools work in laboratory settings to detect degradation, and size pitting, measure biofilm thickness, and provide compositional information. However, they also concluded that the tools typically required dedicated offsite facilities and a high degree of operator skill. They also commented that the tools have limited ability for rapid evaluation and are prohibitively expensive.

So, while these testing tools are useful in a laboratory setting, their nature precludes general frontline operations, particularly in older or remote facilities. Further development is required to refine these tools to reduce their costs, simplify their use, and demonstrate their effectiveness in field conditions., operator skills and untested in the field.

While early detection is desired, pitting inspection presents a significant challenge during its initiating and metastable phases as there is very localized metal loss. Recent investigations into electrochemical noise have been used to detect pit initiation and measure its progress (Chandrasatheesh et al., 2014). Though these newer techniques hold promise, for now, non-destructive inspection must rely on conventional methods.

2.7.1 Conventional NDT Methods

Non-destructive testing (NDT) techniques evaluate materials, components, structures, or systems without damaging the original or in-service structure. In contrast, non-destructive evaluation determines the fitness-for-purpose of equipment by methods that do not endanger its fitness. Applying these definitions to corrosion, NDT would find the presence of corrosion while NDE would not only find the corrosion it would also involve its sizing.

The technique or analysis may be qualitative or quantitative. The most common methods are visual inspection (VT), magnetic particle inspection (MT), liquid penetrant inspection (PT), eddy current (ET), radiographic testing (RT), and ultrasonic inspection (UT). The intent of NDT is to identify and potentially size degradation. Conventional NDT alone cannot determine the type of cause of degradation. Additional forms of surveillance and/or testing, such as molecular microbiological methods are required to determine the cause of degradation.

Provincial or Federal regulations, along with the equipment operator's requirements, define the criteria for In-service inspections.

2.7.1.1.1 Visual Inspection – VT

The most basic and common form of inspection method is VT. Most codes and standards require that VT supplements all other NDE techniques. (API 510, API, ASME BPVC Section V, CSA W59) The inspector looks to verify compliance with regulatory codes/standards and look for potential signs of degradation to ascertain the equipment's fitness for service (Cawley, 2001). The technician relies on visual indicators and aids such as magnifying glasses, additional lighting, and basic measurement tools to observe damage, degradation, alignment, and cracking. VT may be performed at macro and micro levels, using various tools. VT of a component or equipment typically occurs before/during/after surface cleaning to evaluate indications.

The effectiveness of visual inspection depends on the surface conditions, access, lighting arrangements, and tools (Demsetz & Cabrera, 1999). In process systems, internal visual inspection begins after the system is drained and made safe for inspection. During an in-service inspection, the objective is to capture data for current and future assessment purposes. Allowing the user to confirm and predict the equipment's serviceable life (Clifford, 2010; Inspection & Servicing Requirements for In-Service Pressure Equipment Rev 6 Issued 2009-05-29, 2009).

2.7.1.1.2 Magnetic Particle Inspection – MT

It is a surface NDT method used in inspecting ferromagnetic materials. A magnetic field is applied to the material. Surface discontinuities that are transverse to the field create breaks or leakage in the area and draw in magnetic particles (Inspectioneering, 2024).

A related technique is the magnetic flux leakage (MFL) technique. A magnetic field is applied, and the leakage field is monitored. Changes in the amount of leakage may indicate corrosion, pitting, and wall loss (Inspectioneering, 2024).

2.7.1.1.3 Liquid Penetrant Inspection – PT

This is another surface inspection NDT method that relies on capillary action. As its name suggests, a liquid penetrant is applied to a surface. The liquid is then drawn into surface-breaking indications via capillary action. After a dwell period, excess surface penetrant is removed, and a developer is applied to draw out the penetrant in the discontinuity and produce a surface indication. The indications produced are much broader than the actual flaw and are therefore more easily visible (Cawley, 2001).

2.7.1.1.4 Eddy Current – ET

Eddy current inspection is another surface NDE method based on electromagnetism. AC is passed through a conductor coil which produces a magnetic field in and around the conductor. When another electrical conductor is brought into close proximity to this changing magnetic field, current will be induced in this second conductor resulting in eddy currents. Surface discontinuities, like pitting, oriented normally to the surface, will hamper the flow of current, changing the magnetic field (Cawley, 2001).

Defects in materials cause interruptions in the eddy currents that an inspector interprets (Cawley, 2001). Additionally, materials can be identified as electromagnetic inspection tools that can be used to measure conductivity, permeability, and dimensional features (Simpson, 2018).

2.7.1.1.5 Volumetric NDE - Radiographic Inspection (RT), and Ultrasonic Inspection (UT)

As the name suggests, radiographic inspection involves passing radiation generated by gamma or x-rays through a material to create a shadow of the material on a film or detector. Areas of increased density appear brighter and lower density appears darker.

Ultrasonic inspection leverages the fact that sound travels through materials at a velocity that depends on the mechanical properties of the medium. As sound travels through the material, it interacts with its features and deficiencies that cause the sound to be scattered, reflected, echoed, or attenuated. UT applies these principles and properties by transmitting high-frequency sound through a material. The response is monitored by an NDT technician who can evaluate the response. UT is used for defect identification and sizing, dimensional measurements, and determining material properties (Iowa State University, Center for Nondestructive Evaluation, 2021).

2.7.2 Reliability of NDT

The reliability of NDT is a function of the largest flaw that could be missed or the smallest flaw that can be detected during an inspection. To compare how reliable an NDT method is we use the probability of detection (POD) curves. These curves plot the probability of detection versus flaw size detected. In comparing NDT methods, the probability of detection at 90% with a 95% confidence interval is typically used (Ahmad & Bond, 2018).

Numerous studies have been made regarding the reliability of NDT methods (Crutzen et al., 1999; Førli, 1990; Mcgrath et al., 2009; Nichols & Crutzen, 1988; NIL, 1986). The goal was to determine the reliability of the NDT method based on its probability of detection. A number of these studies have been summarized by the Health and Safety Executive (Visser, 2002). The objective of the summary was to obtain quantitative information on the probability of detection of NDT methods to support probabilistic defect assessment and FFS evaluations. What these studies have found is that ET is slightly more sensitive to smaller defects than PT. MT and PT have similar sensitivities, though PT is more sensitive to round defects. For volumetric inspection, RT is less sensitive than UT for crack and crack-like defects. MT cannot inspect non-magnetic materials. Given that austenitic stainless steels are non-magnetic, for the purpose of this study MT is not being considered.

One of the results from the Health and Safety Executive was the development of curves for the probability of detection (POD) and probability of sizing (PoS) of defects. All the POD studies suggested that integrity programs should leverage multiple NDT methods.

Furthermore, NDT technician (inspector) competency, the techniques used, and the procedures that are followed all play a role in detecting, sizing, and reporting NDT results (McGrath, 2008).

2.7.3 Implications of NDT to MIC and Pitting Damage

Quantifying the consequence of a piece of equipment is relatively, easily determined. To determine the probability of failure due to corrosion one must categorize the rate of progression or the extent of MIC in the equipment or system. To monitor degradation, one must leverage NDT methods to monitor change. Accurately conveying the risk allows the owner/operator to make decisions about the safe operation of the equipment. Thus, confidence in the reliability of the NDT methods and techniques is required. Typically, as the probability of failure increases, conservatism must be reduced to understand the current fitness for purpose and risk exposure. To lessen the conservatism, we must have confidence in the inspection data gathered. The result is that a higher probability of detection and sizing is required. Higher POD inspection methods provide detailed information to facilitate engineering criticality or fitness for service assessments.

2.7.4 Analysis of NDT & MIC

Intuitively one recognizes that surface NDT methods (VT, PT, MT, and ET) will allow one to detect the damage caused by MIC or pitting. However, these methods may not provide the remaining thickness or size information. In some cases, like that shown in Figure 3 the true size of the damage would remain hidden.

Volumetric inspection is the only non-destructive way to determine if MIC is degrading pressure equipment. Surface methods may identify initiation sites; however, they likely cannot assess cavity sizes. Visual inspection may not identify fine surface pit initiation sites during an internal inspection. Detection is only the first step in mitigating the damage. Understanding the extent of the damage mechanism(s), the amount of damage caused, and the rate of progression within the system or vessel is required to understand and mitigate the associated risks.

The overview of NDT methods and needs for FFS illustrate that current surface inspection techniques and measurements may not be sufficiently accurate to evaluate the effect of pitting and/or MIC. Particularly given that a surface inspection will fail to "see" the details of the cave, especially if there is a pit cover.

Understanding, if current volumetric inspection methods and techniques are sufficient to evaluate the effects of MIC damage on stainless steel, is important to aid in both FFS and risk analysis. At a glance, it seems contemporary literature has not explored this.

The case study in this work intends to compare the various volumetric inspection methods, radiographic and ultrasonic inspection, and some of their more common techniques in their ability to detect and size MIC damage on a stainless-steel plate.

To begin understanding the capabilities of volumetric inspection techniques to detect MIC pitting, a case study was conducted on a test plate to compare the various volumetric inspection methods. Radiographic and ultrasonic inspection, and some of their more common techniques, were used on the test plate to assess their ability to detect and size MIC damage on a stainless-steel plate.

3 MIC Damaged Test Plate

3.1 Introduction

In a previous section, it was highlighted that fitness for service assessments for pitting damage that leverages inspection from the opposite surface requires sufficient resolution. The implications are that the non-destructive testing must be sufficiently detailed to understand the quantity, size (length, width, and depth) of the pitting and its relationship to adjacent pits. To demonstrate the resolution of NDT methods this work has leveraged a test plate from an austenitic stainless steel hot water tank.

The plate was part of the lower head of a hot water tank operating at 76°C. It had been in service for less than 4 years. The return line piping to the hot water tank failed due to fine pinhole leaks. Failure analysis, including genomic testing, identified the source of the MIC that initiated the failure as being several Mn oxidizing bacterium types. The test plate was then inspected using radiographic and ultrasonic NDT methods.

3.2 Test Plate

For the test plate, see Figure 1Figure 4, was taken from a section of a MIC damaged pressure vessel measuring 150 x 250 mm. The plate was from a 0.25-inch (6.3 mm) coil of an ASTM SA240-13 Grade 316L, that was NACE MR0175 compliant. The actual plate thickness was measured at 6.26 mm. The material was solution annealed at a temperature of 1038°C then water quenched before being put into service. The vessel was fabricated in accordance with ASME BPVC, Section VIII, Division 1; and CSA B51.

The chemical analysis identified in the material test report, and validated during the failure analysis the plate was consistent with that of an austenitic stainless steel. Chemical properties of the plate can be found in Table 1

Table 1 The chemical analysis per ASTM A751.

C%	Cr%	Cu%	Mn%	Mo%	N%	Ni%	P%	S%	Si%
0.0183	16.6875	0.4045	1.250	2.0135	0.0571	10.0750	0.0290	0.001	0.2875

Similarly, the mechanical properties of the test plate from the material test report were consistent with a grade 316L, austenitic stainless steel. Mechanical properties can be found in Table 2.

Table 2 Mechanical properties of the stainless-steel plate.

UTS (MPa)	0.2% YS	Elongation (50mm) %	Hardness RB
612.94	339.29	47.93	86

Figure 4 A section of a MIC damaged pressure vessel plate seen from the outside surface is used for the case study.

The plate has three pits that were detected via NDT, these are labelled as pits 1, 2, and 3. Prior to the removal of the plate, pit 3 had been excavated to a depth of about 2mm and it resulted in an oval gouge with axis lengths of approximately 10mm by 12mm.

3.2.1 Methodology

VT, UT, and RT were performed on the plate as shown in Figure 25. All the non-destructive testing was performed by inspectors certified in the NDT method in accordance with ISO 9712. Documentation of the results was performed by the author in consultation with the NDT technician. NDT was performed in accordance with the general principles of ASME BPVC Section V - Non-destructive Examination (American Society of Mechanical Engineers, 2023), though it should be highlighted that this standard does not address in-service inspection requirements. Inspection of the plate was not performed blind; inspectors could see some of the damage to the plate. As such, the inspectors were aware of where they could see or expect a signal response. This would not necessarily be the case if performed in the field.

Two volumetric NDT methods were performed on the test plate, radiographic and ultrasonic inspection.

3.2.1.1 Radiographic Inspection

Both gamma and x-ray computed radiographic (CR) methods were used to test the plate. In both instances, iridium plates were used for image reception. Inspection was performed in accordance with ASME BPVC Section V. Exposure times were based on the technician's experience.

3.2.1.2 Ultrasonic Inspection

Ultrasonic inspection was performed using manual ultrasonic techniques using single-crystal, dual-crystal, and array probes. Calibration reflected a typical field setup and was performed by using a 316L stainless-steel thickness calibration block, known as a step wedge. For each type of probe, calibration involved maximizing the signal to 80% of the full-screen height (FSH) for the first back wall echo. The screen range was then set to the first back wall echo. For scanning an additional 6 dB was added.

For the conventional probes (i.e., trials 1 through 5) a manual scanning technique across the plate was used. The scanning technique is representative of what is performed in the field. After scanning the largest MIC colony on the plate was inspected using the same probe. To reduce the variation in results, the same technician performed all the manual ultrasonic inspections. Calibration was performed using the same calibration block and the same ultrasonic instrument, a Sonatest Veo3 using the software version 4.40.

3.2.2 Inspection Results

Prior to the volumetric inspection, a visual examination of the test plate was performed to help support the interpretation of the NDT. The visual inspection identified three distinct pits and one area where pits were initiated. Pits 1, and 2 and the initiating pits (identified early) were labelled on the test plate. As shown in Figure 5 pits 1, 2, and 3 could be seen visually. Pit 3 had a length of approximately 15 mm, a width of approximately 12 mm, and an approximate depth of 2mm measured using a pit gauge.

Figure 5 Visual examination of the internal surface of the test plate. Pits 1 and 2 are highlighted pit 3 is the large pit in the bottom centre of the plate.

The size and depths of pits 1 and 2 could not be measured as their diameters were too small to measure accurately without the use of magnification.

3.2.2.1 Radiographic Inspection (RT) Results

The use of computed radiography detected pits 1, 2, and 3. The resulting radiographic image is shown in Figure 6. Pit 1 was measured with a length of 7.7 mm and pit 2 with a length of 4.7 mm. The subsurface length is much greater than what is visible on the surface. Subsurface pitting is also evident at pit 3. The visually identified pitting shown in Figure 5 is not evident in this radiograph. It is presumed that its shallow depth prohibits sufficient contrast for the pits to be seen in the image (film).

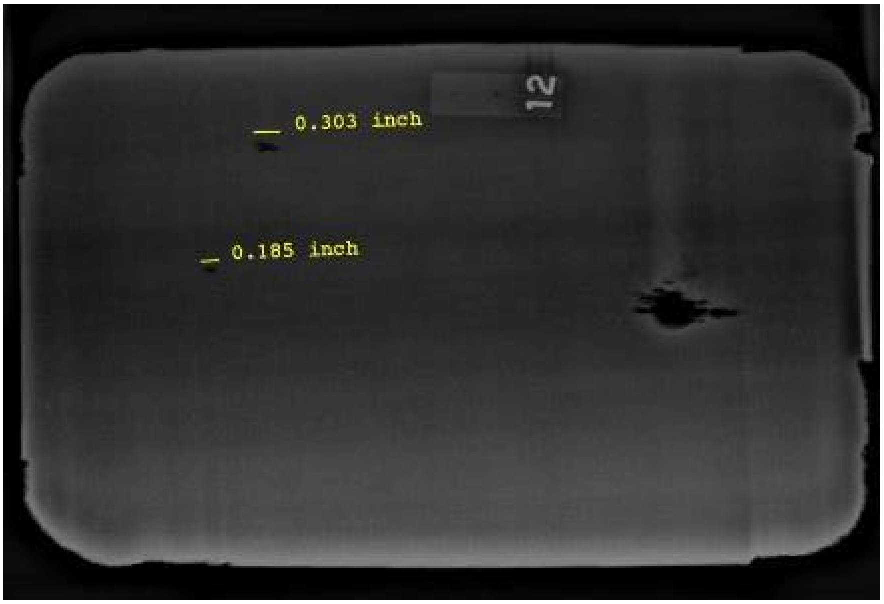

Figure 6 Radiographic image of the plate taken using an X-ray source.

3.2.2.2 Ultrasonic Inspection (UT) Results

In all UT trials pits 1 and 2 were not initially detected using UT. This was expected as pits 1 and 2 were below the probability of detection limits for manual UT with the chosen probes. With the PAUT probes pits 1 and 2 were detected; however, only after review of the data set was the technician able to see both sides of the plate.

3.2.2.2.1 Effect of Ultrasonic Variables

Prior to discussing the results of the testing, it should be noted that UT procedures and techniques balance several of the critical variables that affect UT results. A mnemonic that is taught to new UT technicians by senior technicians and was shared with the author is shown in Figure 7.

f ↑	**P**↓	**A** ↑	**D** ↓	**S** ↑	**C** ↓	**R** ↑	**λ** ↓	**N** ↑
Frequency	**P**enetration	**A**ttenuation	**D**ivergence	**S**pread	**C**rystal thickness	**R**esolution	wavelength	**N**ear zone/field

Figure 7 A mnemonic is used in NDT/NDE training to highlight the relationship of variables in UT.

Though the origin of this widely used mnemonic is unknown, the intent is to facilitate the inspection technicians' understanding of the interrelation of the UT variables when selecting the probe frequency and diameters for their inspection activity. Balancing these variables allows the technician to select equipment to detect, size, and evaluate findings.

3.2.2.2.2 Trial #1 - Single Crystal, 1” (25.4 mm) 2.25 MHz Probe

In trial #1, the plate was scanned with a gain set to 80% full-screen height (FSH), see Figure 8. As can be seen in Figure 9, there was very little sound loss between the first and second back wall. There was no discernable indication from MIC at all, no reduction in the back wall because the probe diameter is very large compared to MIC.

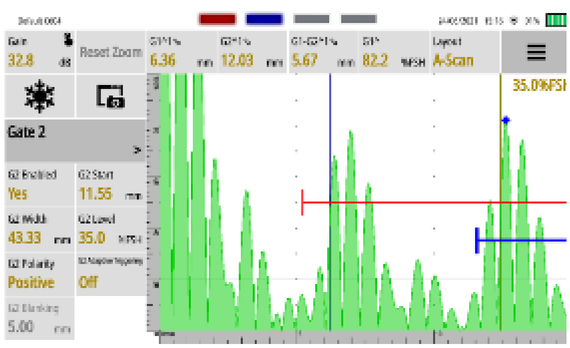

Figure 8 Back wall echo (BWE) set at 80% full-screen height.

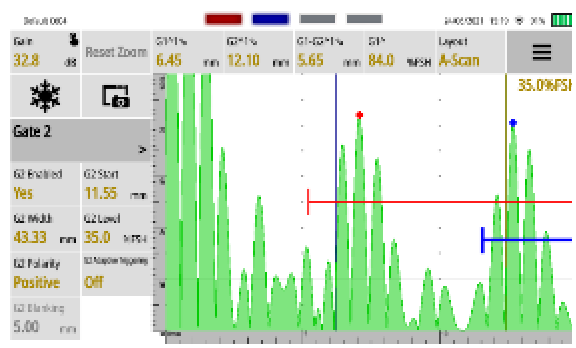

Figure 9 Signal response at MIC damage. Red and blue dots show the location of the first and second back wall echo respectively.

3.2.2.2.3 Trial #2 - Single Crystal, ½” (12.7 mm) 5 MHz Probe

As the diameter of the probe decreased and the frequency was increased, there was a reduction of back wall echo due to the increased attenuation and beam spread. This is shown in Figure 10. As can be seen in Figure 11 there is some signal response; however, it could easily be mistaken for noise. For all intents and purposes, the MIC could not be detected. The best estimate at the pit depth based on the signal response was 1.1mm.

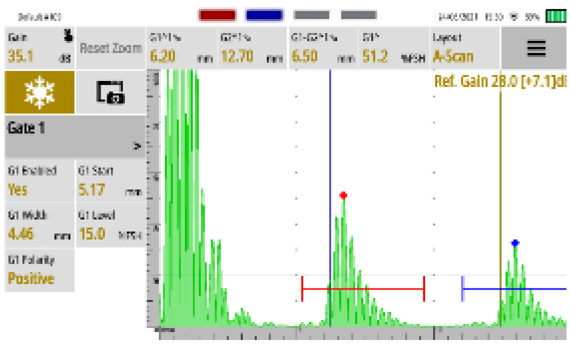

Figure 10 MIC pit response with an additional 7.1 dB to the reference gain. The first and second BWE are the red and blue dots respectively.

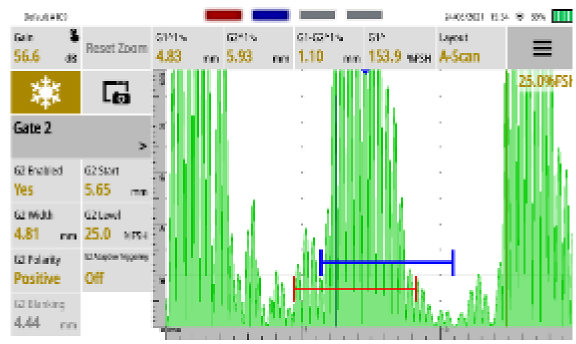

Figure 11 MIC pit signal response compared to the noise at 10%. One could not distinguish noise from pitting.

3.2.2.2.4 Trial #3 - Single Crystal, ¼" (6.35 mm) 5 MHz Probe

Figure 12 is the signal response from calibration. Figure 13 shows the signal response from the MIC pit. The drop in sound level can be seen just before the first and second BWE. The signal is at a relatively low amplitude. The pit depth was measured at 1.3mm.

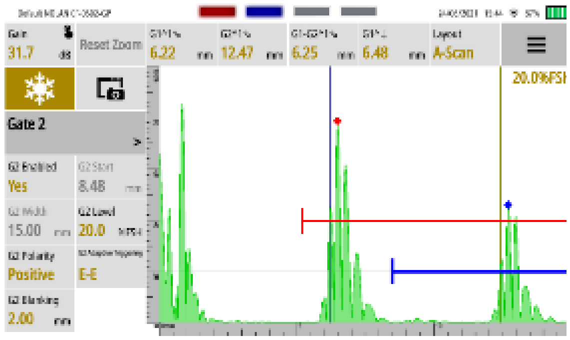

Figure 12 Signal response with a BWE set at 80% FSH.

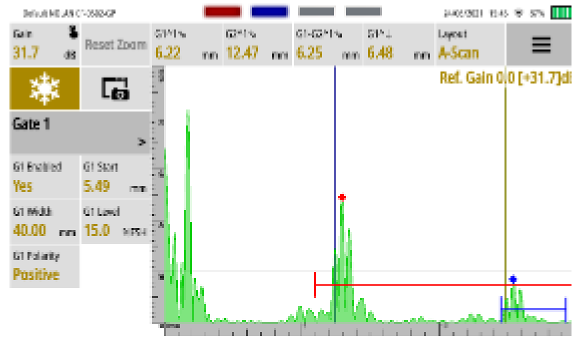

Figure 13 MIC response with a BWE set at 80% FSH. Pitting is visible in the front of the signals at low amplitude.

3.2.2.2.5 Trial #4 - Single Crystal, ⅛" (3.2 mm) 10 MHz Probe

Like trial 3, Figure 14 shows the signal of the uncorroded material. Figure 15 shows the signal response at pit 3. Using the smaller diameter, higher frequency probe, the signal generated by the MIC pit is easily detected. Unlike trial #3, the signal overshadows the BWE. The pit depth was measured at 1.6mm.

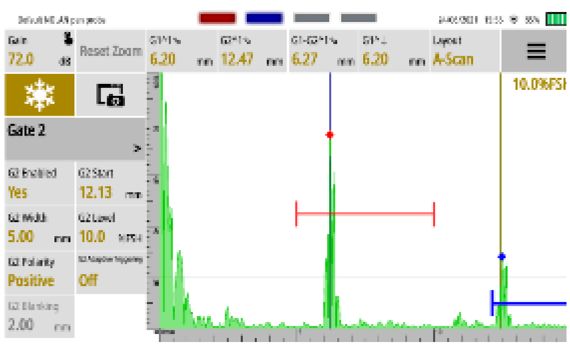

Figure 14 Signal response with a BWE set at 80% FSH.

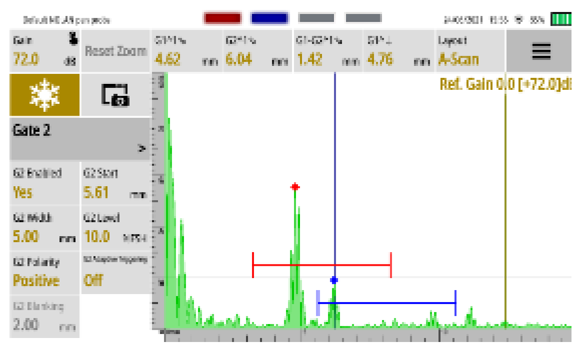

Figure 15 MIC response overshadows the BWE. Second BWE is significantly attenuated.

3.2.2.2.6 Trial #5 – Dual Crystal, 0.434" (11 mm) 5 MHz Probe

Figure 16 shows the unaffected material at calibration. With the dual crystal probe there is a signal response; however, to evaluate the signal the gain had to be increased. With this probe response to the MIC is attenuation of the signal, see Figure 17. The resulting signal shown in Figure 18 allowed the pit to be measured at 1.12 mm.

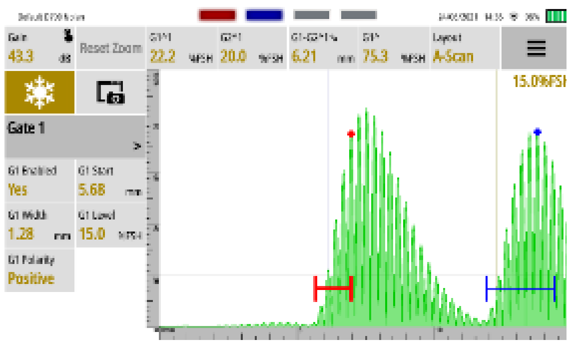

Figure 16 Initial BWE set at 80% FSH.

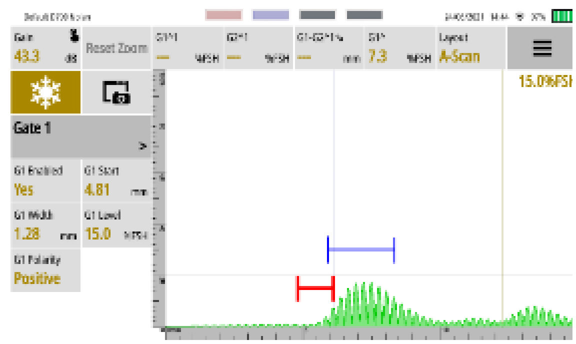

Figure 17 Signal response at MIC pit. No reflection with a reduction of second BWE.

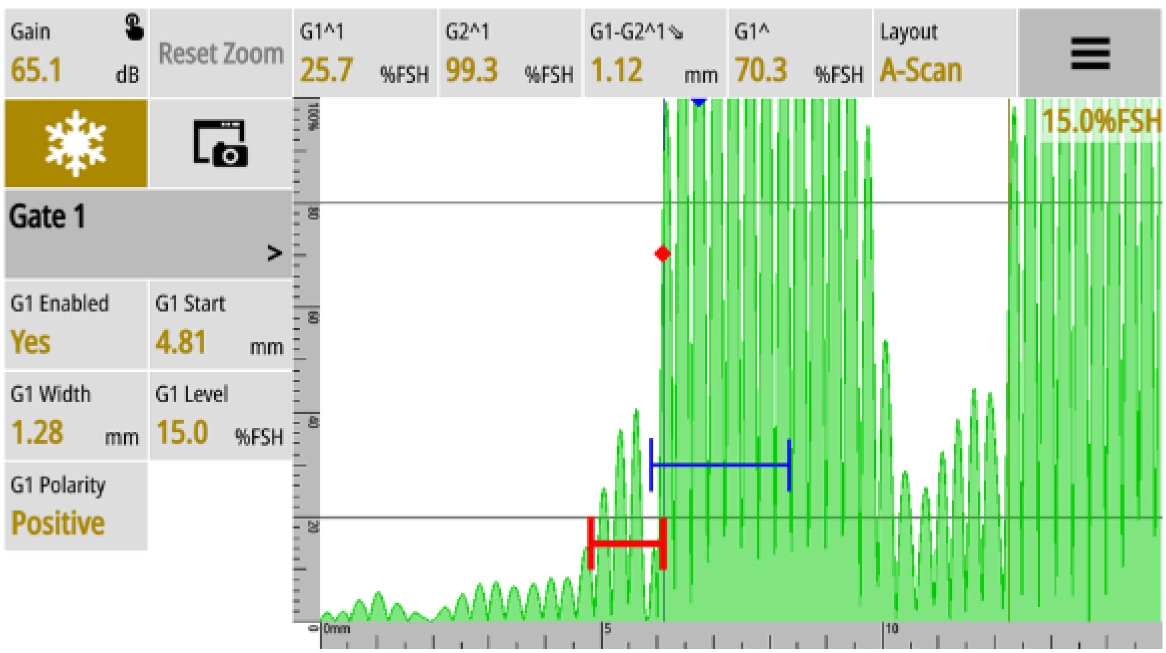

Figure 18 MIC pit response compared to noise at 10%.

3.2.2.2.7 Trials #6 to #8 – Phased Array Ultrasonic Inspection (PAUT) – General

PAUT allows the user to customize the screens and provide different views of the ultrasonic inspection. For the purposes of this work, the screen setup shown in Figure 19 was used. The intent of this setup is to allow wall sizing of MIC pit depth using the Lscan and A-scan which facilitates detection using the second BWE as it creates a “shadow” effect of MIC pit instead of MIC pit itself, see Figure 20.

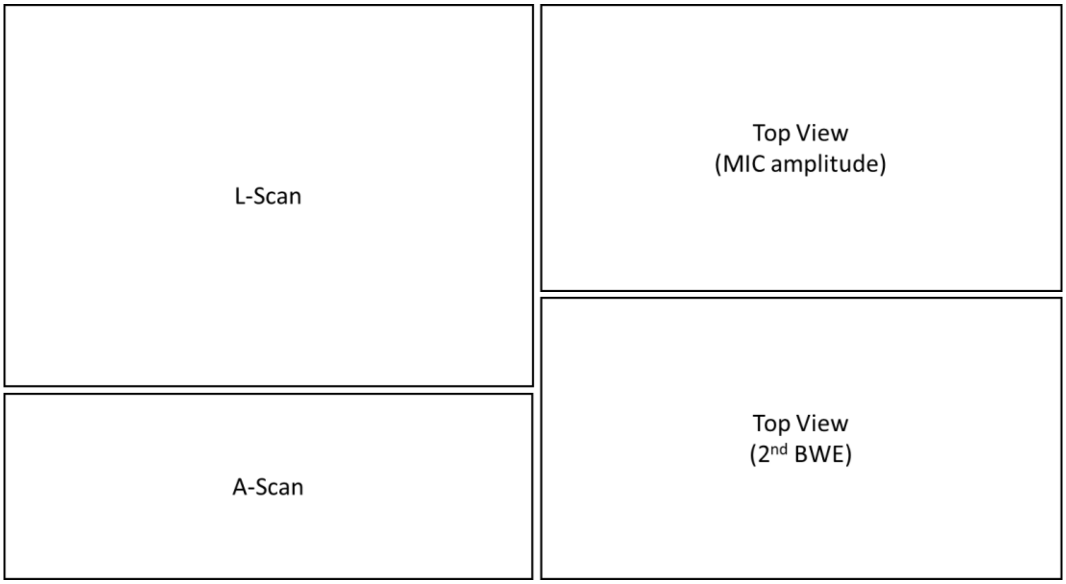

Figure 19 An overview of the screen setup on the PAUT instrument.

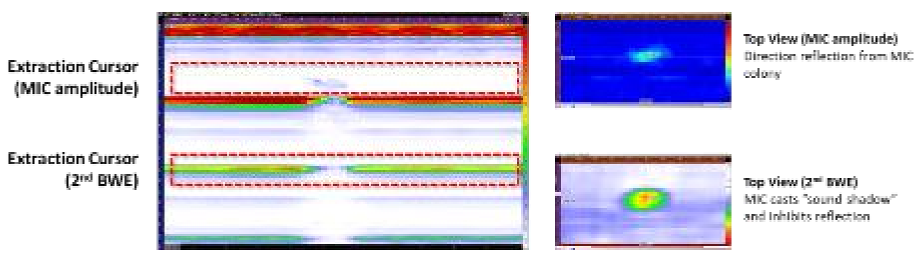

Figure 20 A further breakdown of the screens used for the PAUT scans.

Figure 21 to Figure 24, inclusive show the PAUT signal responses caused by pit 3. The various screenshots demonstrate an improved resolution of the pit with a higher frequency and smaller pitch in the probe.

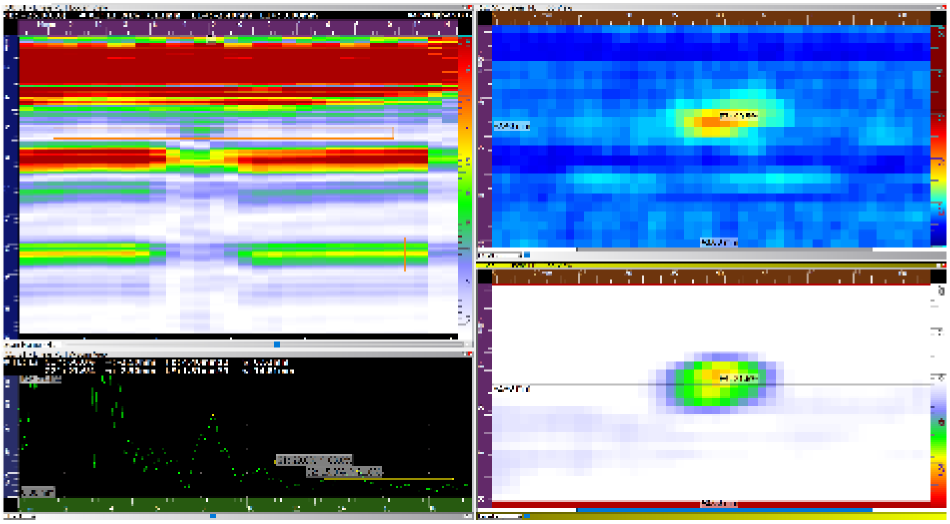

Figure 21 Trial #6 - A 2.25 MHz PAUT probe with a 1 mm pitch.

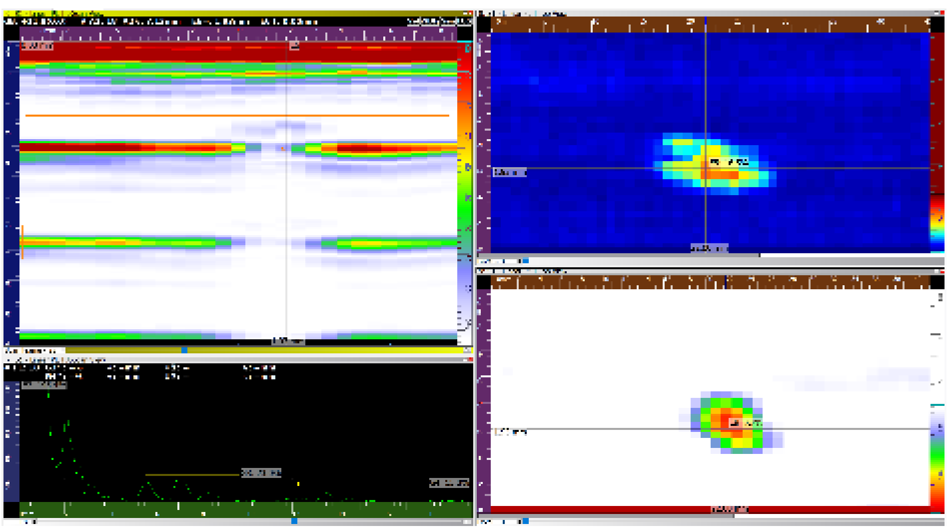

Figure 22 Trial #7 - A 5 MHz PAUT probe with a 0.6 mm pitch.

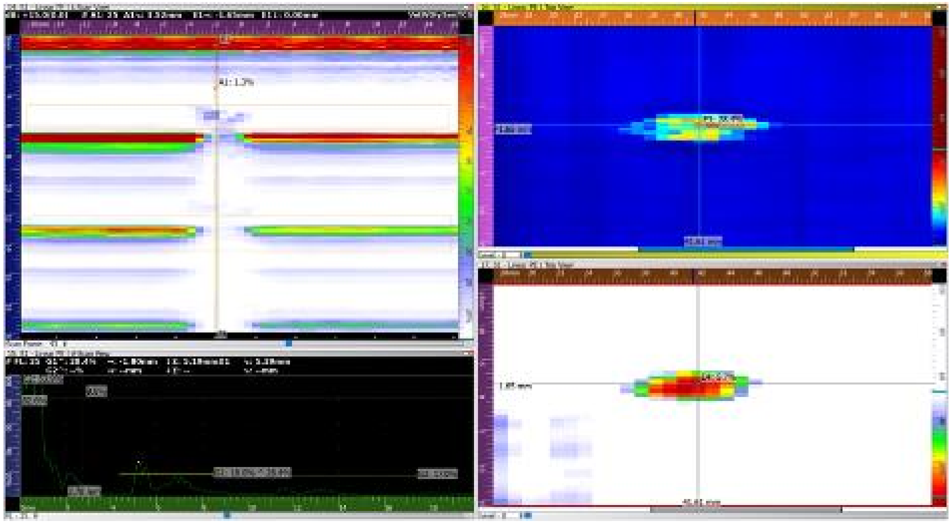

Figure 23 Trial #8 - A 10 MHz PAUT probe with a 0.3 mm pitch.

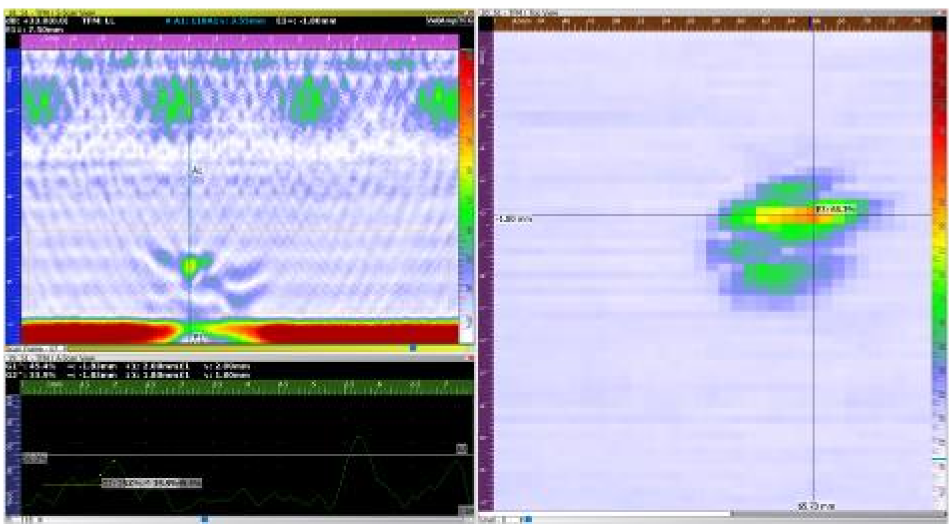

Figure 24 Trial #9 - A 5 MHz PAUT probe with a 0.6 mm pitch using the Time Focus Method (TFM).

Regardless of the PAUT probe used the results provide a better understanding of the pit damage and size. It was noted in trial #6 that the lower frequency 2.25 MHz probe had an extended dead zone at the entry surface as seen by the red banding before the first back wall echo. As such, accurate through-wall sizing was not possible. In trial #7, there is a smaller dead zone and an improved signal-to-noise ratio providing a much clearer signal. Which results in a better C-scan image of the MIC. In trial #8, the 10 MHz probe has a smaller dead zone and a signal-to-noise ratio that provides a clear signal. However, there are some light blue bands likely caused by the austenitic structure of the stainless steel. The results of the ultrasonic inspections are summarized in Table 3, below.

Table 3 NDT results from the inspection of the MIC degraded plate.

Trial	*Type*	*Model*	*Probe* *Description*	*Probe Dia.* *(mm)*	*Frequency (f)* *(MHz)*	*MIC Detected?* *(Y/N)*	*Pit L x W x D* *(mm)*	*Signal to Noise Ratio*	*λ = V/f* *(mm)*
1	Single	C604	1 inch	25.4	2.25	N	N/A	NA	2.54
2	Single	A109S	½ inch	12.7	5	Y	? x ? x 1.1	4:01	1.14
3	Single	CF-0502-GP	¼ inch	6.35	5	Y	? x ? x 1.3	4:01	1.14
4	Single	T-481-4507	⅛ inch (pen)	3	10	Y	? x ? x 1.6	>16:1	0.57
5	Dual	D790	0.434 inch	11	5	Y	? x ? x 1.1	4:01	1.14
6	PAUT	2.25L32-A32	1.0mm pitch	1	2.25	Y	10 x 5 x ?	4:01	2.54
7	PAUT	5L32-A31	0.6mm pitch	0.6	5	Y	13 x 4 x 1.6	>20:1	1.14
8	PAUT	10L64-A12	0.3mm pitch	0.3	10	Y	13 x 5 x 1.9	>20:1	0.57
9	TFM	5L32-A31	0.6mm pitch	0.6	5	Y	15 x 4 x 1.9	6:01	1.14

3.2.3 Discussion of UT Results

The manual scanning with conventional UT in trials 1 to 5 present (probes 1-5) was impractical for detection. The technician described the effort as looking for a "needle in a haystack", small indications were easy to miss. Small signal changes could be missed when monitoring the manipulation of the probe. So, while MIC was detected using most of these probes, it was primarily a function of knowing the damage was there. Since the technician was looking for some form of signal response. Sizing the damage depth using manual scanning worked, though there was a variation in the depth. The depth of pit 3 measured from 1.1 mm to 1.9 mm, versus 2 mm measured. These results suggest that when conventional UT locates pitting or MIC damage, the pit should be sized using a pen probe (e.g. probe used in trial #4).

With the advanced PAUT probes, using encoded scanning it was noted that a 5 MHz probe has a lower signal-to-noise ratio than the 10 MHz probe. This is presumed to be a function of the austenitic steel's grain structure. It was also noted that the use of the Focussed Method (TFM) improved the ability to size the depth.

PAUT (i.e. advanced UT methods) provide more accurate pit sizing, including depth compared to the single crystal probes.

3.3 Discussions of Case Study NDT Results

RT was only able to size the width and length of corrosion. However, it was able to detect pits 1 & 2, unlike the other volumetric methods. The depth of corrosion could not be determined. However, it is possible this could be overcome to a degree if a thickness comparator had been used.

Advanced UT techniques and the use of higher frequency probes result in improved detection and sizing of the degradation. The results also highlight the importance of not only the NDT method but also the associated techniques, particularly in detecting fine pitting and MIC.

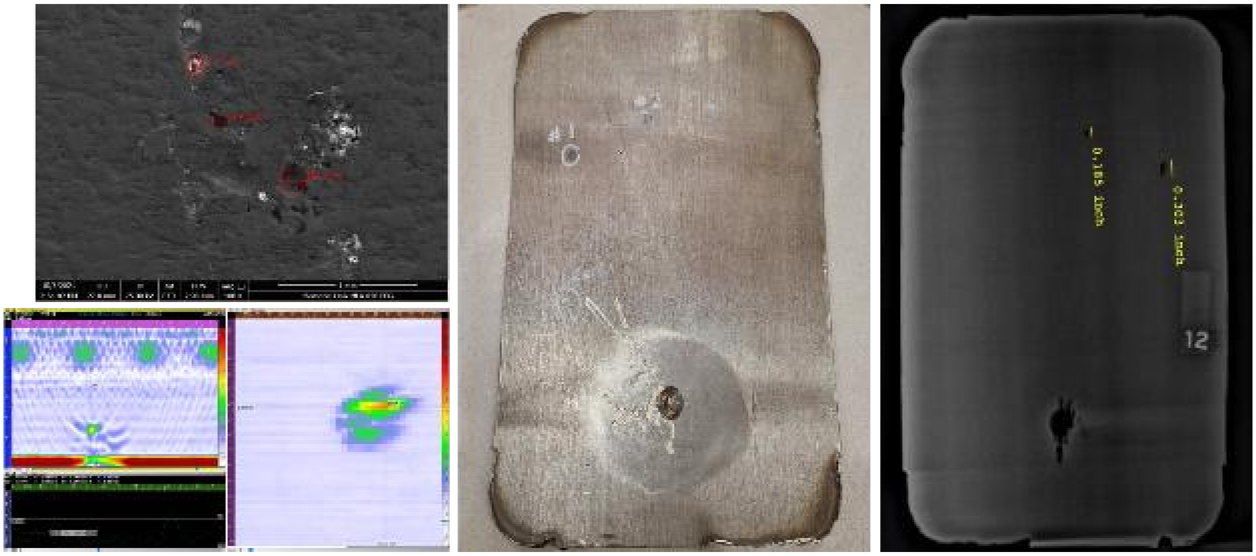

Figure 25 NDT methods that were used in evaluating the plate degraded by MIC, a) Scanning electron microscope of the surface, b) visual inspection, c) radiographic inspection d) ultrasonic inspection methods.

The approach used for this case study represents the approach that would be followed in industry and the techniques that would be applied in the field. The inspection of the test plate highlights that the NDT method and technique must consider the level of detail and accuracy required. It also reinforces the results of the Health and Safety Executive's recommendations that multiple NDT methods are required. Though this work suggests that once found with one NDT method and specific technique it is important to monitor change using the same NDT methods and techniques. Changes in one of the variables will influence the results. PAUT provides better data on the sizing of corrosion damage.

Based on the limited study, the probability of failure portions of risk profiles must consider the relationship between NDT methods and techniques. They also must consider the ability to detect and size corrosion damage for FFS activities. More advanced methods, like PAUT and computed radiography, provide better information than conventional thickness readings. A proposed correlation between POD confidence, NDE/NDT methods and corrosion type based on this case study is shown in Figure 26. It is recognized that there are techniques to approximate the depth of a defect using RT using density; however, the results would be subjective. So, any data obtained would not likely be used in fitness for service calculations.

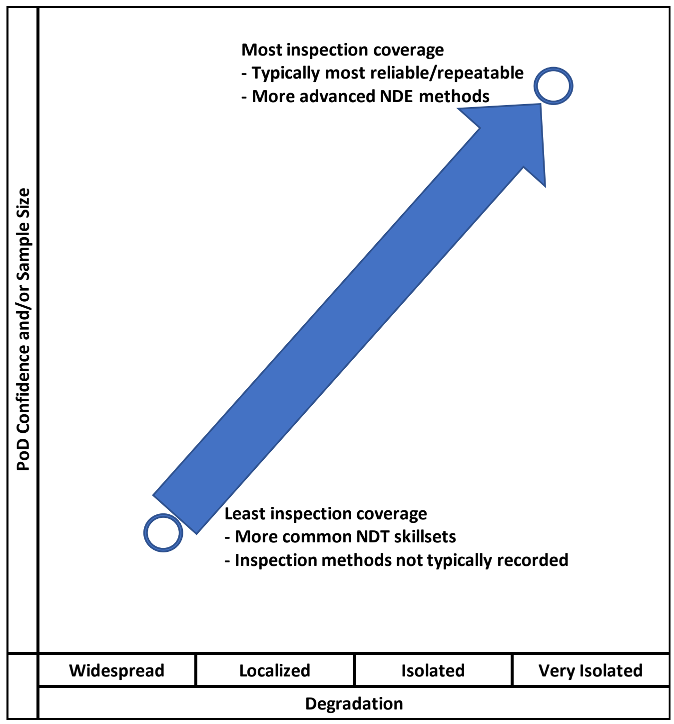

Figure 26 A sketch of POD Confidence versus degradation based on the inspection of the MIC plate sample.

The results also reinforce the need for an understanding of NDT methods and techniques when using the inspection results.

3.4 Conclusions from the NDT Case Study

Based on current NDT reliability data advanced NDT methods, like PAUT should be used for detecting and sizing MIC or pitting damage. Where possible multiple NDT methods should be used to validate findings.

There can be variation in sizing even within one NDT method (e.g. UT or RT). When monitoring a defect's size, the same NDT method, technique, and, where possible procedure should be followed.

Caution should be used in relying on NDT measurement data during level 3 FFS as there likely is some variation from the actual pit depth.

4 Corrosion Risk Assessment

degradation caused by MIC presents challenges to academia and industry. Though there are tools to model corrosion behaviour and assess the fitness for service of the components evaluating and/or modeling the risks to the integrity of a facility presents a challenge. Consider that if corrosion, especially less understood forms such as MIC, is not fully understood by experts it is not likely the management of a process facility will fully appreciate its challenges or potential risks. For the effect of corrosion to be appreciated by management, the potential impact on the organization must be clearly understood. In 2016, the National Association of Corrosion Engineers (NACE) initiated the IMPACT study (International Measures of Prevention, Application, and Economics of Corrosion Technologies). The authors had the remit to establish best practices by examining the role of corrosion management in industry and government. One of the conclusions of this study was a need to change corrosion decision-making. Without appropriate corrosion prevention and control, corrosion-related catastrophic events cannot be avoided.

As a result, a corrosion risk assessment model that addresses three of the concerns outlined in the NACE Impact Report was developed. The first objective is to provide a model that uses a methodology like those used in financial and risk assessments. The second is to provide a simplified model for those in decision-making roles. The third is to provide a tool that allows the integration of corrosion management elements into the overarching management system.

Kaplan & Garrick (1981) suggested that risk analysis answers the following three questions:

I. What can happen? (i.e., what can go wrong?)
II. How likely is it that it will happen?
III. If it does happen, what are the consequences?

To answer these questions for a corrosion management program, owners and operators would need to answer the following three questions:

1. What is the risk caused by degradation?
2. What is driving degradation risk?
3. How effective are maintenance strategies or activities that are intended to manage, mitigate, or correct degradation?

4.1 RISK

CSA/ISO 9000:2016 defines risk in terms of a combination of the consequences of an event (including changes in circumstances) and the associated likelihood (as defined in ISO Guide 73:2009, 3.6.1.1) of occurrence.

Traditionally, recommended practices like API 580 and API 581 are used to answer these questions for risk-based inspection programs and to guide corrosion practitioners. As discussed, the degradation caused by MIC cannot be predicted with current technologies. While research and modeling are improving the understanding of MIC, we do not have a fully refined, accurate model. As such, how are risks managed and how are they easily communicated to stakeholders? Detailed knowledge of degradation mechanisms, safety and risk principles, and asset management tools are not necessarily common to all industries.

Bow-tie analysis is commonly used to assess both the threats and consequences of a hazard or undesired event. This includes both the events "leading to" and the consequences "leading from" the occurrence are considered (Kim & Vinnem, 2015).

Since the 1970's Bowties have been used to communicate and prioritize process operation and maintenance activities to ensure risk is as low as reasonably practical (ALARP). Bow ties are considered reliable tools for presenting the causes and consequences of a failure (Saud et al., 2014). Bow tie diagrams are a method of documenting forward and backward analysis techniques such as failure mode effect analysis (FMEA), Fault Trees, Event Trees, and hazard and operability study (HAZOP) or other techniques (N. Leveson, 2015).

This top-down, graphical approach developed by Bell Laboratories, in New Jersey, was adapted for reliability studies in the nuclear industry; and has been adapted to various other engineering applications (Ebeling, 1997). The method works as follows:

1. A top event is identified, along with any boundary conditions.
2. The possible events and related faults causing the top event are identified.
3. The resulting tree allows the user to evaluate the potential combination of events that result in the top event.

4. If the level of detail is adequate and there is reliability or failure data available, then the probability of the top event can be calculated to provide a quantitative assessment.

To develop a practical model that incorporates MIC in risk assessment, a bow tie analysis combining Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) was needed. Figure 27 illustrates the proposed bowtie.

The left side of a bow tie considers preventative measures leading to an undesired event and is the focus of FTA. The right side of a bow tie focuses on the mitigative measures that lead to multiple consequences, after the initiating event and represents the ETA.

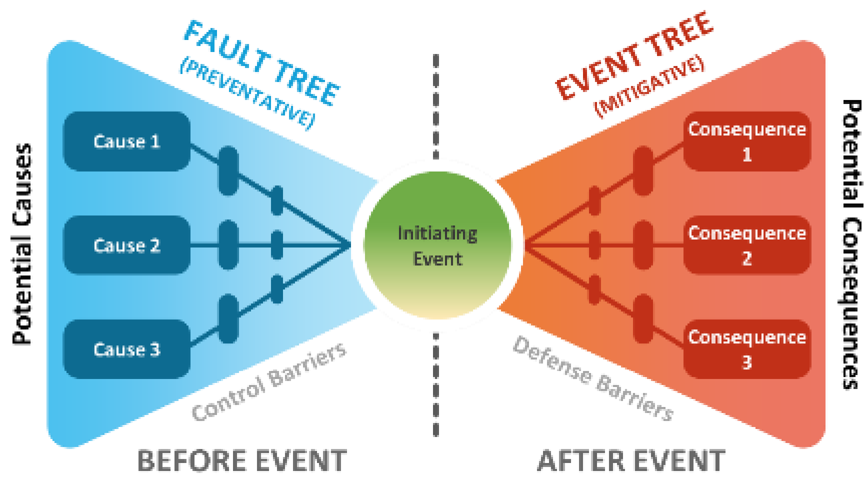

Figure 27 An overview of a bow tie, showing the fault tree on the left and the event tree on the right.

4.1.1 Fault Tree Analysis (FTA)

A fault tree method is a method of determining the causes of an accident whereby a logic diagram displays the interrelationships between a potentially critical event in a system and the causes of this event. FTA is one of the most used techniques in risk and reliability studies (Kim & Vinnem, 2015). An FTA is constructed using simple logic statements.

In FTA the objective is to understand the control barriers that prevent the initiating event. It starts by asking the question, "What are the potential causes of the initiating event?". Once the potential causes are identified, the control barriers preventing the cause are identified. Control barriers are identified by asking, "How do we control the hazard or prevent it from occurring?". If the failure probabilities of the barriers are known, then the probability of the initiating event can be calculated provided the failure events are all independent.

4.1.2 Event Tree Analysis (ETA)

An event tree analysis evaluates potential outcomes that may result following a process upset or equipment failure known as the initiating event. An event tree begins with an initiating event and reviews the plausible sequences of events that describe potential consequences, accounting for both the successes and failures of the safety functions as the accident progresses (Department of Chemical Engineering, 2000). The sequence of events in an ETA must remain the same (N. G. Leveson, 2019).

ETA asks questions like, "What happens after the initiating event?". It then proceeds to ask what the potential consequences are?"; and proceeds to ask, "How do we mitigate these consequences?". These questions then allow the identification of mitigation strategies. Event trees are binary and represent when a system is safe or unsafe (N. G. Leveson, 2019).

4.1.3 Advantages And Disadvantages of Bow Tie Analysis

One of the benefits of using a bow tie is that it allows us to provide a visual understanding of the cause and effect of an initiating event. Its simplicity provides a structured approach without needing to be fully versed in safety and risk management. Bow tie analyses are typically qualitative, not quantitative, and provide visibility on both preventative and mitigative measures. As such it facilitates managing risks (Sneddon, 2017).

While bow tie analysis (BTA) is a useful tool, without historical or operational data it is possible for scenarios that lead to the top event being missed. It is also founded on the very basic assumption that causes are linear, so the controls in bow ties must be independent. Bow ties alone will not identify which controls are the most important. As such they should be considered subjective. One should also remember that in many cases non-linear causality may be an important consideration in certain industries (N. G. Leveson, 2019).

4.2 Corrosion Case Studies

A bow tie using FTA and ETA provides a potential mechanism to communicate the complexity of corrosion mechanisms like MIC. Examining three documented corrosion failures from different industries allows the development of a potential fault tree for the event that considers a loss of containment due to material degradation. The case studies were chosen to reflect the range of complexity of pressure systems and the maturity of integrity programs for pressure equipment in various industries.

4.2.1 Loy Lange - A Box Company Pressure Vessel Explosion

In 2017, there was a large steam explosion at the Loy Lange Box Company. The failure of a 910 kg, carbon steel, semi-close receiver vessel (SCR) caused by oxygen corrosion launched the vessel through the roof of a building killing one worker and injuring another. The resulting vessel impact and shrapnel killed three members of the public (Clancy & Long, 2019). The vessel materials were chosen based on non-corrosive service, so carbon steel with no corrosion allowance.

The United States Chemical Safety and Hazard Investigation Board (CSB) investigated the incident. They found the primary cause of the failure to be oxygen corrosion of the lower head of the vessel. Corrosion progressed on the lower head of the vessel until it failed, resulting in the boiling liquid expanding vapour explosion that launched the vessel.

In the investigation, the CSB found that prior to the incident, chemical surveillance had identified the insufficient use of an oxygen scavenger. Furthermore, the operational procedures used facilitated the introduction of small amounts of dissolved oxygen into the SCR, and the facility experienced at least three known leaks in the SCR.

In practice either the monitoring was not undertaken, thus allowing the extent of the problems to remain hidden, or the monitoring recommended by the audit was undertaken but no action was taken on the results. They also found that the company did not have any programs that would have helped identify, analyze, or mitigate the potential risks and learn from previous incidents.

4.2.2 Conoco Phillips Humber Refinery

In 2001, there was a large fire and explosion in the saturate gas plant portion of a refinery in the United Kingdom. A line containing flammable gas under pressure failed releasing a gas cloud. The gas cloud ignited resulting in a fire and explosion. The cause of the fire was erosion/corrosion of a 6" nominal pipe size, carbon steel line near an injection point. The extrados of the elbow thinned until it could no longer contain the required pressure. In addition to proper material selection as part of the Owner's corrosion control program, the owners had performed a process hazard analysis (PHA). In the PHA for the plant, the designers had identified that design changes to the plant could result in loss of containment issues. Which led to the recommendation of implementing a procedure to control site modifications.

Measurements of the failed pipe section found that it had thinned from 7 mm to 0.3 mm. Furthermore, the post-failure inspection found that thinning was consistent with erosion/corrosion at the injection point. The Health & Safety Executive (HSE) investigation also found:

- There had been previous failures on an upstream section of the line. Follow-up inspections didn't include the failed elbow.
- The management of change (MOC) process was not effective. The impact of design changes, flow changes, or other safety considerations related to the inspection frequency or corrosion rate were not considered.

- They also noted that “there were no criteria established to indicate at what level of risk it would become unacceptable to justify continued operation of the [Saturate Gas Plant] SGP.

The consequences of the fire and explosion were quite serious. There were people injured, properties within 1 km of the facility were damaged and the facility was shut down for several weeks. The company was fined approximately € 1.1 million. Additionally, prior to start-up, the plant was required to perform additional inspections of safety-critical pressure equipment, costing over €10.16 million and needing 86 inspectors to execute (HSE, 1997).

4.2.3 Prudhoe Bay Pipeline Failure

In March of 2006, a 6 mm hole caused by internal corrosion of a 34” diameter, crude oil carbon steel pipeline resulted in a crude spill of over 803400 L. The operator, BP had pigged the pipeline in 1990, 1998 and 2004. The results of the latest pigging revealed a higher-than-expected corrosion rate. The output of the resulting risk-based assessment was to perform a smart pig of the line during the summer of 2006 (Committee on Energy and Commerce, 2007).

Subsequently, BP shut down the pipeline to perform detailed inspections of all the piping systems in the area. In the eastern line, the smart pig results identified sixteen (16) anomalies. Wall loss estimates of between 70 and 81% were found in twelve (12) locations of the pipeline.

Although the failure analysis of the pipeline was never shared publicly, it was reported during the congressional investigation that MIC and/or corrosion under deposits were the likely culprit(s) (Committee on Energy and Commerce, 2006). During the investigations, the following items were reported via media articles, congressional investigations, and regulatory reports:

- BP personnel had raised concerns that corrosion management was insufficient.
- Corrosion management programs such as corrosion inhibitors, corrosion coupons and inspections were likely insufficient to detect and monitor /these forms of corrosion.
- the lack of a formal, holistic risk assessment process that was sensitive to changing operations and conditions in the field.
- The pipeline had been in operation for 30 years.

In addition to the spill, the operator of the pipeline had a significant loss of reputation and was heavily fined. The resulting financial losses included a fine of $20 million dollars in addition to various lawsuits and the costs associated with the loss of production (Jacobson, 2007).

4.2.4 Case Study Discussion

Although the materials involved are not stainless steel and degradation mechanisms are different the sequence of events is relevant for MIC and stainless steel. In each of the three case studies the measures to detect and mitigate corrosion risks have some commonalities. In each event, there were signs of corrosion before the catastrophic failures. In two cases, there was prior loss of containment within the associated systems. In all cases, the corrective maintenance response did not target or consider the degradation mechanism. This ignores other process safety considerations (operating standards, contractor management, work practices, management of change, etc.) that may have contributed to the events. This aligns with other studies into corrosion that have determined that the primary risk initiation factors were the age of equipment, preventative maintenance, corrective maintenance on previous leaks, and management of change (Kim & Vinnem, 2015) (Haugen et al., 2011).

In each of these case studies the pressure equipment materials were chosen based on the expected service conditions. Corrosion allowances were defined based on expected service conditions and there was conservatism in the designs that would and/or did provide the ability for fitness for service evaluations. In fact, in the BP case study, FFS was performed and a decision to continue to operate was made.

Since corrosion is a function of a metal returning to its natural state as the material reacts with its environment it cannot be eliminated. It must be managed through a combination of monitoring and mitigation treatments. The objective of a corrosion mitigation program is to reduce degradation rates to an acceptable level of risk. Otherwise, as these three case studies have shown there can be significant consequences, particularly if it occurs in pressure equipment in operation. The probability of material degrading without intervention is one (1).

In each of these events, the owners and operators of the equipment were or should have been aware of the risks. The use of BTA would provide some guidance and could have facilitated a better decision-making process. The use of the bow-tie model would have shown the corrosion risk profile increase over time from the material selection and metal loss.

4.2.5 The Fault Tree

Risk is a function of probability and consequence. In the case of material degradation, and specifically, corrosion resulting in a containment issue, the consequences of downtime, environmental containment issues and accidents are relatively quantifiable. Particularly comparing the probability of corrosion. There is a commonality in the fault tree in the three case studies. Were the probabilities of corrosion resulting in a catastrophic incident in three scenarios communicated to stakeholders? Did they fully appreciate the risk(s) even though inspection and maintenance activities were being performed in all the case studies.

The fault tree in Figure 28 was developed after considering the literature review of MIC, and the case studies in the previous section. For corrosion not to result in containment issues, one must identify the degradation and there needs to be a maintenance program. Maintenance programs leverage both preventative and corrective maintenance activities to monitor, mitigate and/or rectify degradation. If there is an effective maintenance program then the probability of degradation resulting in a failure is not one, presuming that there is an ability to detect and identify degradation and that maintenance activities are performed and are effective. The effectiveness of maintenance presumes that there is an understanding of the true cause of degradation and appropriate corrective measures are selected. To identify the cause of the degradation one must understand both the internal and external degradation mechanisms. It is this model that forms the basis of the primary events for the fault tree.

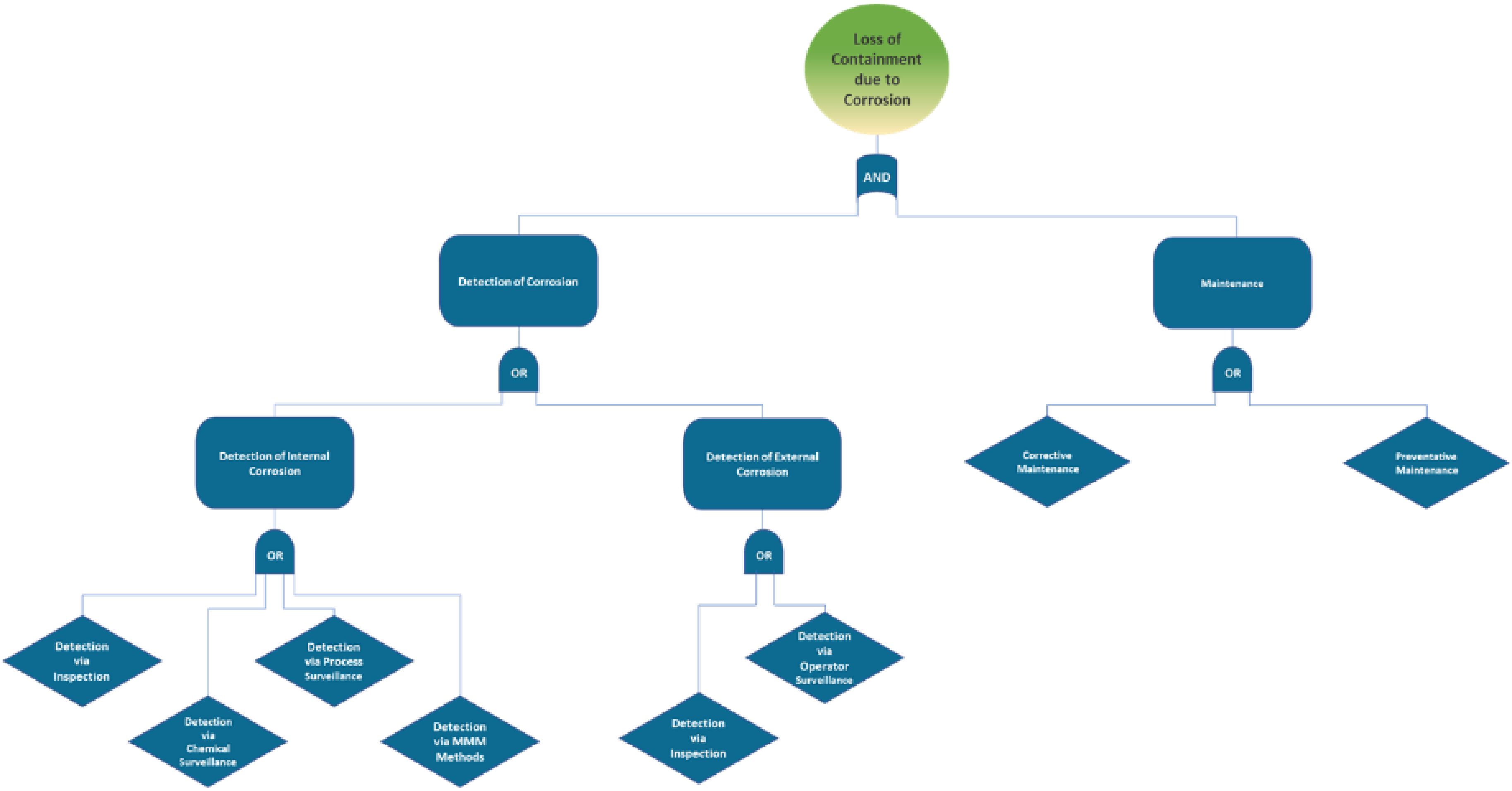

Figure 28 The proposed fault tree for the loss of containment due to corrosion.

4.2.6 The Event Tree

The purpose of the event tree (Figure 29) is to identify and/or evaluate the barriers that mitigate the effects of the initiating event. In each case study material selection and corrosion allowances were the initial barriers to mitigate corrosion damage. Leveraging the case studies previously discussed led to the creation of the event tree. Event trees can facilitate the identification of the critical barriers and evaluate their effect on the overall system failure. To simplify their use, failure mechanisms are typically analyzed individually presuming they have the same initiating event (Loback et al., 2010).

The analyzed case studies demonstrated that the mitigative measures involved were material selection, a decision related to corrosion allowance, and applicable design standards. The conservatism in the chosen design codes allows fitness for service evaluation. In each case, the degradation was accepted despite a reduction in thickness after some form of fitness for service assessment. It is proposed that this common sequence of events and their associated mitigative measures form the basis for the proposed event tree.

North American pressure equipment is designed to various codes, primarily the American Petroleum Institute (API), the American Society of Mechanical Engineers (ASME), and the Canadian Standards Association (CSA). In all these codes materials are chosen to contain some conservatism to address potential acceptable weld deficiencies. As such, operators of pressure equipment will typically ask whether the equipment is safe to operate. If so, how long and under what conditions? As part of the initial design, designers consider the need for a corrosion allowance (CA). To answer this question, once the corrosion allowance is surpassed, they will typically leverage API 579 as it is referenced by numerous codes and standards and provides a methodology for this type of analysis (ASME, 2016).

To standardize fitness for service (FFS) approaches industry developed API 579. The intent of FFS is to provide a structured approach to evaluate the continued fitness for service of equipment, particularly when flaws, design standards, or more severe operating conditions are present. The standardization of the approach provided by API 579 provides transparency for review by local jurisdictions (Wintle, 2003) (Anderson & Osage, 2000).

The use of API Recommended Practice 579 has three levels of assessment to support an FFS that progresses sequentially from level 1 to level 3. These levels of assessment typically reflect the associated complexity of the calculations as conservatisms are reduced. As such level 1 is the simplest level of assessment and level 3 is the most detailed. Typically, a level 3 assessment requires the use of finite element analysis and an understanding of the behaviour of the degradation mechanism. Generally, the level of assessment is proportional to the level of damage progression (Anderson & Osage, 2000; Greg Garic, 2019).

The first step of any pressure equipment design is to select a material that is appropriate for the application. The basis for material selection is to understand the intended lifecycle of the material. The base inputs are the conditions during the startup, typical operating, shutdown, and of course, during potential process upsets. This may include the types of coatings and/or linings that are used. The combined reliability requirements and experiences of the designers and owners determine the material(s) to be selected (CCPS, 2012) (Bahadori, 2017a).

Once the material is selected the second step is to consider a corrosion allowance. This additional material allowance is based on the intended service life and the estimated corrosion rate for the lifecycle service conditions (Bahadori, 2017b).

It is when these barriers fail that the steps of API 579 are followed resulting in the potential of level 1, 2 or 3 evaluations.

If one applies this sequence to an event tree, then the potential consequences are shown in Figure 29. If corrosion occurs, the material selection has failed. There is still a barrier of a corrosion allowance, which presuming is greater than 0, ensures that there should be no issues related to safe operations.

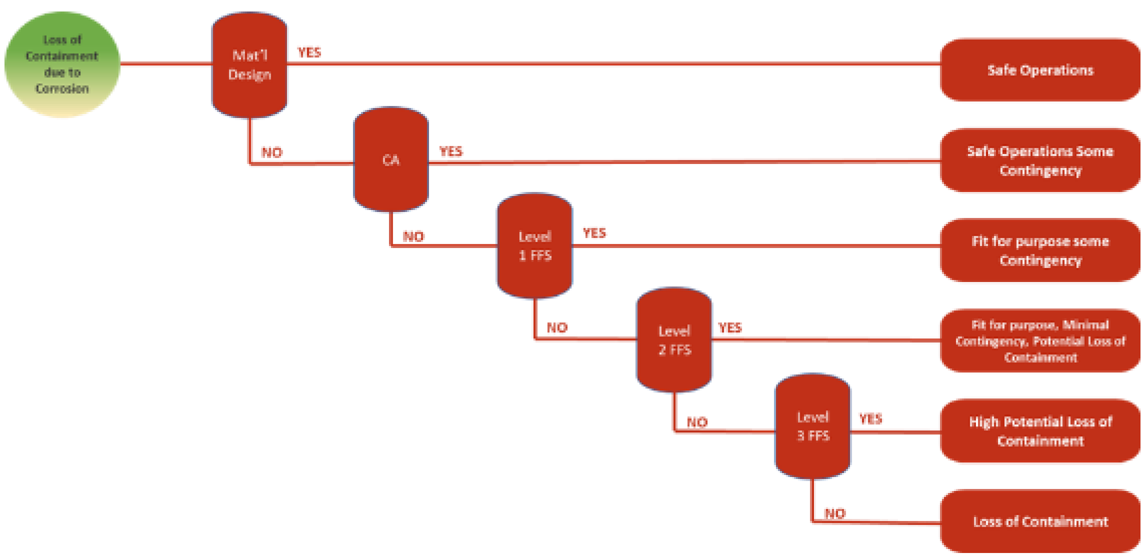

Figure 29 A fitness for service event tree.

4.3 The Resulting Bow Tie

The resulting bow tie is shown in Figure 30. The fault tree is intended to be simplistic to facilitate its use and understanding. It allows the undeveloped portions of the fault tree to be customized for the user. Individual users may leverage inputs from their bespoke, integrity, and/or corrosion management systems that support their specific operations. Similarly, the event tree is constructed of simple, binary logic statements. Again, the intent is that data from the performance of the corrosion management system is taken to populate the tree. The basis of the BTA is that the corrosion management system leverages the failure probabilities for all the boxes and that the failure events are all independent.

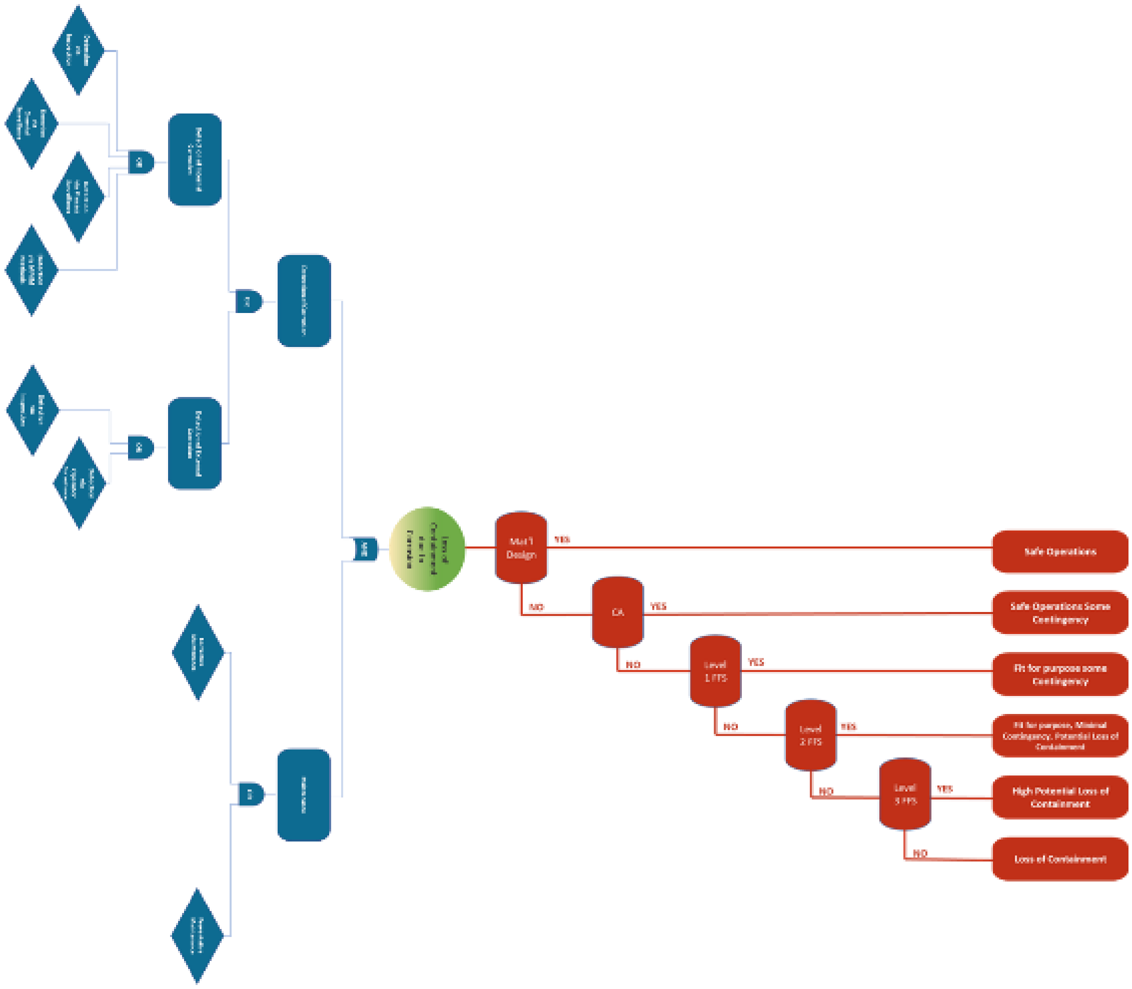

Figure 30 The resulting bow tie corrosion assessment model was developed from the fault tree and event tree.

4.4 Using the Corrosion Bow Tie Model

Bow-tie analysis is useful in both qualitative and quantitative assessments. Qualitatively it visually demonstrates the link between cause and consequence through a series of barriers. Coupled with a risk matrix the bow tie can be used as a foundation to qualitatively define risk levels. Alternatively, the bow tie can be used quantitatively to quantify consequence risk levels based on probability failure rates of the associated barriers. The output is then compared against organization-specific risk tolerances to validate that the general risk levels to personnel are either broadly acceptable region, conditional (ALARP) region or unacceptable region.

ALARP is an acronym for As Low as Reasonably Practicable. The intent of the ALARP principle is that risks have been mitigated to balance risk tolerance against cost, time and amount of control needed to eliminate the risk. Unfortunately, outside the legal context, there is no specific framework or criteria to be used to clearly show ALARP. The responsibility lies with the operators and regulators to demonstrate risks have been mitigated and that they balance safety against cost, time, and trouble. The criteria used to judge ALARP is based on a common law judgment Edwards v National Coal Board [1949] 1 All E. R. 743, which stated, "' Reasonably practicable' was a narrower term than 'physically possible', and implied that computation must be made by the owner in which the degree of risk was placed in one scale and the sacrifice involved in the measures necessary for averting the risk (whether in money, time or trouble) was placed in the other. If there was a gross disproportion between them – the risk being insignificant in relation to the sacrifice – the onus on the owner was discharged.".

To perform a quantitative bow tie analysis, probabilities are assigned to each of the events. It should be highlighted that the effectiveness of maintenance activities, including any associated management of change processes is a topic on its own and the contributions to this portion of the tree are beyond the scope of this thesis. For the purposes of this model, it is presumed that maintenance is effective at remediating the degradation.

The intent of each model is that the performance of the integrity program is represented by the preventative side of the bowtie, created by the fault tree. Initially, it is the performance targets of the management program are represented the mitigative side of the bowtie, created by the event tree. Similarly, the probability assigned to each event of the fault tree is the performance target effectiveness of the related integrity program. An option is to leverage the performance standard(s) target for the system to represent the probability the performance standard would be met. Given that the intent of this model is to apply to any process system, the maturity of the integrity programs or management system will vary. As such each organization must tailor how they calculate the probability of the underdeveloped event and set performance targets for the integrity program.

As the integrity program is executed the probabilities are updated based on the criteria defined by the integrity program. The study of the change in corrosion risk profile then allows decisions for maintenance and/or integrity programs.

4.5 Monte Carlo Simulations

During World War II, scientists working on the Manhattan Project coined the term "Monte Carlo" simulation. Its premise is to input statistically appropriate variables into a mathematical model and collect the output. The resulting output values provide information regarding the possible outcomes of an uncertain event (Stevens, 2022).

A Monte Carlo simulation leveraging the model developed from the preceding section is used to evaluate the effect of changes to the fault tree. The initial probability values used for each event and the fault tree are based on the author's experiences, except where supported by other references. The probabilities can change based on the metallurgy of the system, the process fluids, their operating factors, and other conditions. For the purposes of this fault tree, it has been presumed that 95% of the time planned maintenance activities are successfully completed and that the maintenance activities are effective in mitigating the failure.

To demonstrate the potential of the bow tie analysis using this model a baseline and six additional scenarios were created. For each scenario, a Monte Carlo simulation will be used to calculate the probability and consequences of the BTA. These scenarios show the impact of the corrosion risk of an integrity program based on the integrity program components, particularly the inspection program. The six scenarios are based on the case studies and consider the reliability of the inspection program. The base scenario is reflective of a typical integrity program, the next one that uses inspection with a low (scenario 1), medium (scenario 4), and high (scenario 5) probability of detection; a low POD with chemical surveillance (scenario 2); a low POD with chemical, process, and molecular microbiological methods (MMM) in scenario 3; and, a high POD with chemical, process and molecular microbiological methods (scenario 6). Data for the fault tree can be found in Table 4.

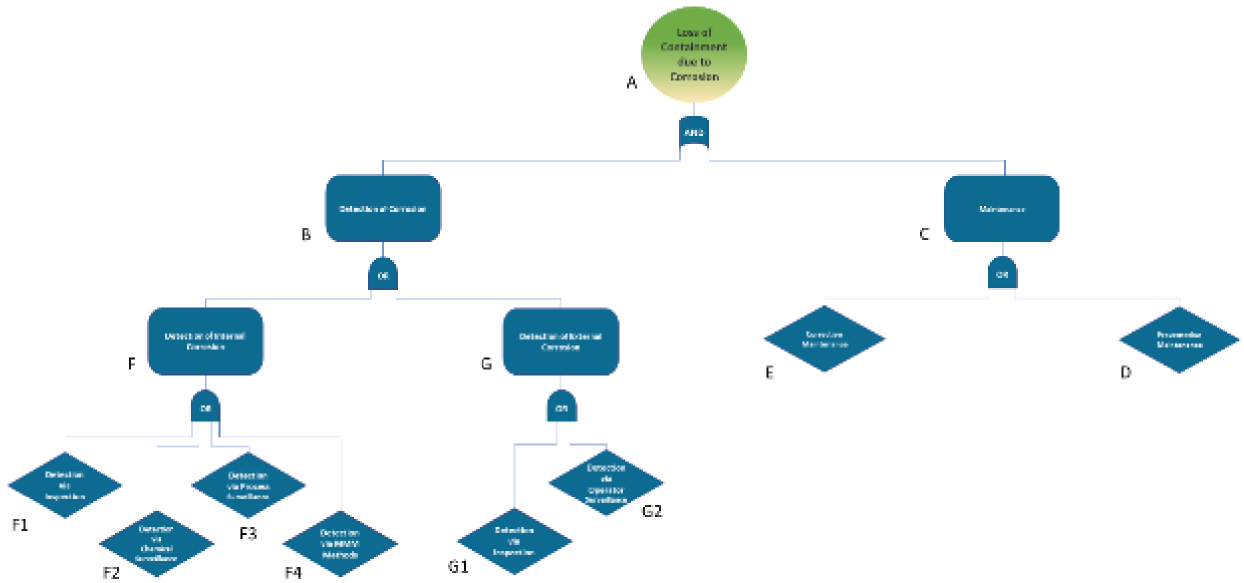

Table 4 The data for the base case scenario that is used in the Monte Carlo simulation.

EVENT	Label	Probability	
PoF of Containment Issue due to Corrosion	A	P(A) =	0.08
Probability to Detect Corrosion	B	P(B) =	0.86
Probability of Maintenance being effective	C	P(C) =	0.10
Probability of Maintenance Being Performed Prior to Containment Issue	D	P(D) =	0.95
Probability of Corrective Maintenance Mitigating Corrosion Driver	E	P(E) =	0.50
Probability to Detect Internal Corrosion	F	P(F) =	0.10
Probability to Detect External Corrosion	G	P(G) =	0.85
Probability of Detecting Internal Corrosion via Inspection	F1	P(F1) =	0.10
Probability of Detection via Chemical Surveillance Program	F2	P(F2) =	0.00
Probability of Detection via Process Surveillance Program	F3	P(F3) =	0.00
Probability of Detection via MMM	F4	P(F4) =	0.00
Probability of Detection via External Inspection	G1	P(G1) =	0.80
Probability of Operator Surveillance	G2	P(G2) =	0.25

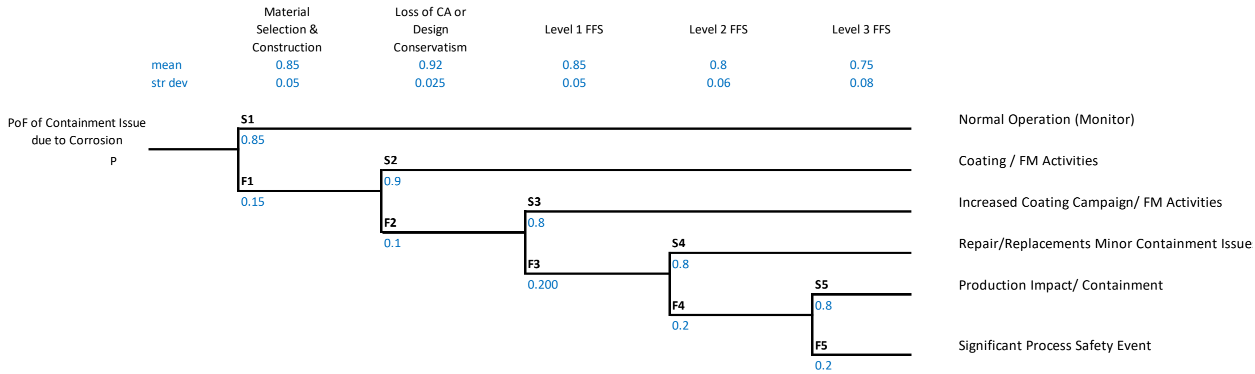

Figure 31 An event tree for the Monte Carlo simulation.

In the base case scenario, a lower effective internal inspection program is used, without any process, chemical or MMM surveillance support. The remaining scenarios are modified to evaluate the impact of the changes to the internal inspection program and the resulting risk. In the first scenario, a chemical surveillance program is added. It should be highlighted that the intent of chemical surveillance is to use chemical sampling to monitor for corrosion products and changes that may indicate corrosion is occurring. Scenario two (2) lower effectiveness of inspection with chemical surveillance is considered. In scenario three (3), lower effectiveness of internal inspection, chemical surveillance, process surveillance and MMM are considered. In scenario four (4) the internal inspection program effectiveness is increased from the base case. In scenario five (5) the internal inspection program effectiveness is again increased to a highly effective program. In scenario six (6), a highly effective inspection program is combined with chemical surveillance, process surveillance and MMM.

For all cases, all other parameters of the bow tie are fixed. A summary of the data used in each simulation can be found in Table 5

Table 5 The data used for the various Monte Carlo simulations.

Fault Tree Component	Base Case	Scenario 1	Scenario 2	Scenario 4	Scenario 3	Scenario 5	Scenario 6
PoF of Containment Issue due to Corrosion	0.09	0.21	0.38	0.44	0.62	0.68	0.84
Probability to Detect Corrosion	0.86	0.88	0.92	0.93	0.95	0.96	0.98
Probability of Maintenance being effective	0.10	0.24	0.41	0.48	0.65	0.71	0.85
Probability of Maintenance Being Performed Prior to Containment Issue	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Probability of Corrective Maintenance Mitigating Corrosion Driver	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Probability to Detect Internal Corrosion	0.10	0.25	0.44	0.50	0.68	0.75	0.89
Probability to Detect External Corrosion	0.85	0.85	0.85	0.85	0.85	0.85	0.85
Probability of Detecting Internal Corrosion via Inspection	0.10	0.25	0.25	0.50	0.25	0.75	0.75
Probability of Detection via Chemical Surveillance Program	0.00	0.00	0.25	0.00	0.25	0.00	0.25
Probability of Detection via Process Surveillance Program	0.00	0.00	0.00	0.00	0.25	0.00	0.25
Probability of Detection via MMM	0.00	0.00	0.00	0.00	0.25	0.00	0.25
Probability of Detection via External Inspection	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Probability of Operator Surveillance	0.25	0.25	0.25	0.25	0.25	0.25	0.25

Changing the parameters of the fault tree while maintaining consistent parameters of the event tree (i.e. mitigative measures) allows the evaluation of the effect on the risk associated with the preventative measures. The resulting Monte Carlo simulations results can be found in Table 6.

Table 6 A summary of the results from the Monte Carlo simulation.

Description of Consequence	Base Case	Low PoD Inspection Scenario 1	Med PoD Inspection Scenario 4	High PoD Inspection Scenario 5	Low + Chem Surv Scenario 2	Low PoD CS, PS & MMM Scenario 3	High POD with Low CS, PS, MMM Scenario 6
Normal Operation (Monitor)	7.81E-01	6.70E-01	4.76E-01	2.64E-01	5.25E-01	3.24E-01	1.40E-01
Coating / FM Activities	1.26E-01	1.08E-01	7.78E-02	4.35E-02	8.48E-02	5.30E-02	2.28E-02
Increased Coating Campaign/ FM Activities	9.42E-03	7.93E-03	5.73E-03	3.18E-03	6.27E-03	3.88E-03	1.68E-03
Repair/Replacements Minor Containment Issues	1.33E-03	1.12E-03	8.09E-04	4.48E-04	8.82E-04	5.49E-04	6.00E+00
Production Impact/ Containment	2.49E-04	2.07E-04	1.52E-04	8.37E-05	1.67E-04	1.03E-04	4.52E-05
Significant Process Safety Event	8.33E-05	6.96E-05	5.07E-05	2.78E-05	5.56E-05	3.40E-05	1.51E-05
Cummulative Risk	9.18E-01	7.87E-01	5.61E-01	3.11E-01	6.17E-01	3.81E-01	6.16E+00
PoF of Containment Issue due to Corrosion	0.92	0.79	0.56	0.31	0.62	0.38	0.16

Evaluating the scenarios using a Pareto distribution, the use of more effective and/or combination of tools results in a greater impact than one or two lower effectiveness.

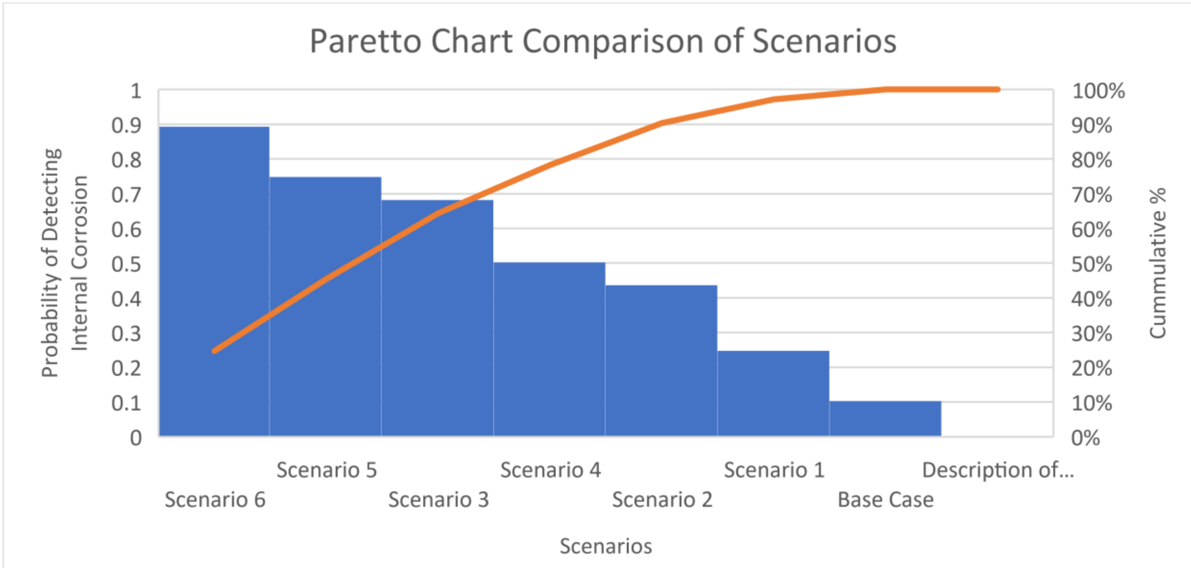

Figure 32 A Pareto chart comparing the various Monte Carlo simulations.

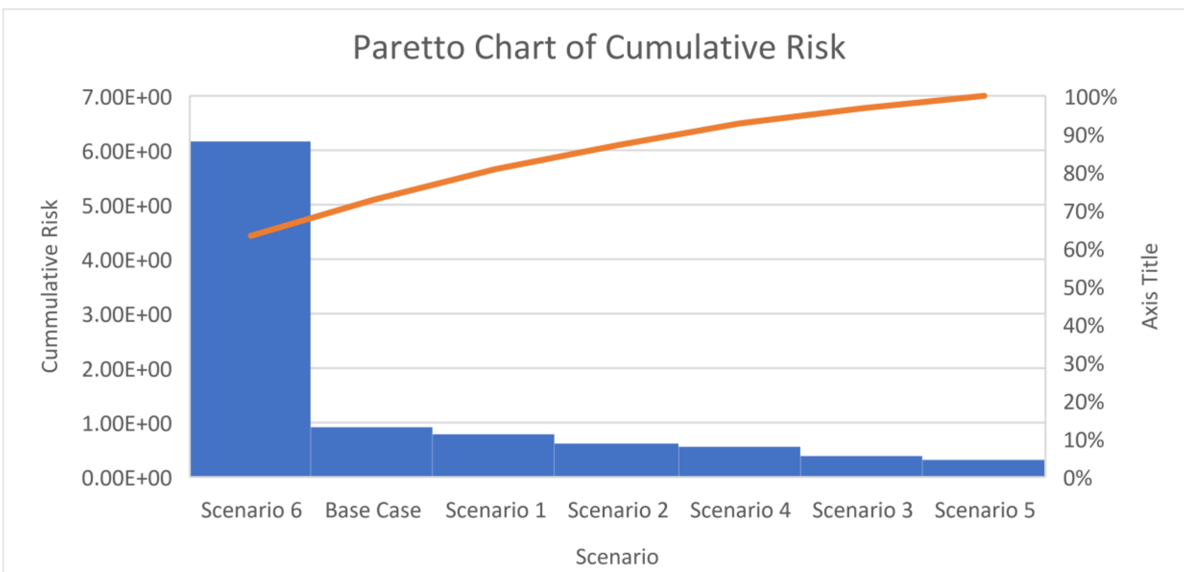

Figure 33 A Pareto chart showing the cumulative risk profiles.

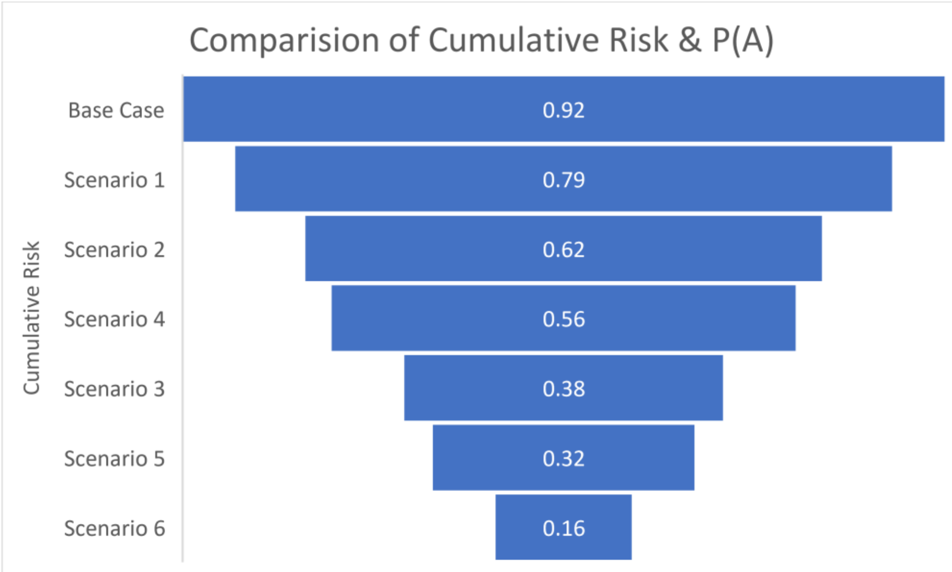

Figure 34 A comparison of the cumulative risk and the resulting probability of loss of containment due to corrosion.

The results of the Monte Carlo simulations on the bow tie demonstrate that the basic activities bolstered using additional integrity surveillance tools such as chemical, process and MMM methods will reduce the risks potentially caused by corrosion.

4.6 Discussion

To demonstrate the use of the proposed model, it was applied to the known failures analyzed as case studies. This will illustrate the risk profile associated with the progression of the corrosion.

4.6.1 Loy Lange

In this scenario, the owner of the facility had no mechanical integrity or inspection program, and they had minimal operational surveillance. This approach to integrity didn't perform regular internal inspections and relied primarily on corrective maintenance to mitigate the risks associated with the degradation of their equipment. It was also found that despite a repair it is likely that the vessel was thinner than the SCR's required minimum thickness. Furthermore, the vessel was designed for non-corrosive service and had no corrosion allowance.

Using the bow tie model for this scenario is relatively straightforward as many of the barriers on both sides of the bow tie are missing. In this case, contributors to the failure are a function of poor preventative maintenance practices (lack of inspection, thorough maintenance/repair), a lack of process surveillance, ineffective chemical surveillance, and a lack of preventative maintenance. On the event tree, there were two mitigative measures removed during design (material selection and corrosion allowance). This leaves the fitness for service barriers, which were compromised based on the findings of the failure analysis (US Chemical Safety and Hazard Investigation Board, 2022). The resulting risk of a significant consequence changes from 1 in 10,000 to a probability of 1 in 100.

4.6.2 Conoco Philips

In this case study, the failure of the elbow was a function of an ineffective inspection program and improper material selection at an injection point that would be subjected to erosion. This is despite previous failures in upstream sections of the piping. Previous inspections had identified pitting was present and monitoring was recommended.

How would the model apply in this situation? In this situation, the model must be used over a period. The length of the time (period) must be aligned with the integrity program cycle. It needs to be considered that the risk profile associated with corrosion will change over time. As the integrity program gathers the inspection data the associated probabilities would be updated into the event tree portion of the model. The resulting risk profile is then updated. Within this model the loss of one preventative barrier results in a 10-fold increase in risk. Mitigation measures could have been explored and evaluated to reduce the risk exposure.

4.6.3 Prudhoe Bay Pipeline Failure

There was a significant inspection and integrity program on the pipeline. Despite this, personnel were still concerned corrosion management was insufficient as the corrosion inhibitors, corrosion coupons and inspections were likely insufficient to detect and monitor this/these forms of corrosion.

Applying the model to the Prudhoe Bay scenario and monitoring the change in reliability of preventative targets and the increase in level 2 and 3 FFS requirements would have highlighted that the RBI assumptions and corrosion management were insufficient. Furthermore, it would have highlighted initial leaks had increased the risk profile associated with the pipeline. Potentially, initiating intervention before the incident occurred.

4.6.4 General Discussion

The various case studies and simulations demonstrate the importance of the user consistently defining the reliability or probability associated with the events within the model. Each RBI and maintenance program will calculate probabilities differently. As such, each organization will have different results for their risk profile, which will change over time. Having a clearly defined basis for defining or measuring the probabilities facilitates monitoring changes in risk profile. The Monte Carlo simulations demonstrate the benefits of the structure. Particularly, if the maintenance and integrity program key performance indicators (KPI) that reflect the user's processes are used to support the probabilities in the model.

The limitation of the model is that how KPIs are defined/developed is based on the user. As such, the user can under or over-inflate the probabilities within the model. Use of the model will demonstrate the probability used is over or under-inflated presuming the KPIs are calculated using the same methodology at the next interval. This will ensure that the decisions being made will be effective. For example, if at year 1, the level 1 FFS probability was set by calculating the Level 1 FFS versus total FFS over the previous inspection period then at year 1 + N, the level 1 FFS probability must be set using the same definitions.

5 Discussion

Corrosion and microbially influenced corrosion are challenging topics. Industry experts and academics are still not fully aligned on the mechanisms. As such detailed models are not typically available or developed for industry.

Leveraging NDT methods and techniques is critical to monitor and measure degradation. The NDT of the MIC degraded plate reinforces that NDT methods and techniques must be selected based on the type(s) of degradation that could be encountered. Using an incorrect NDT method or the wrong NDT technique may fail to detect deficiencies until they grow large enough to be detected. This results in an increase in the risk profile. The increase in risk may or may not be acceptable depending on the process system. It also suggests that higher POD inspection methods are required to detect and/or monitor faster degradation mechanisms. Integrity programs cannot simply rely on inspection and maintenance data. Risks cannot be appropriately mitigated without genomic and chemical testing supplementing inspection data.

The model developed provides a foundation for demonstrating the risk associated with maintenance and reliability programs. As degradation models are developed and maintenance programs are refined or mature the undeveloped events in the model can be expanded and tailored to the industry or organization using the model. For facilities that leverage advanced instrumentation and maintenance systems with robust, consistent data sets there may be an ability to leverage artificial intelligence and machine learning into the risk assessment to provide a more dynamic risk assessment tool.

The model developed provides a qualitative understanding of risk. Consistent use of this risk assessment model will support or enhance decision-making. It can answer questions such as are the maintenance and inspection program keeping up with the risk. What happens when the amount of inspection or surveillance is reduced? The challenge with the model is that it requires a consistent and robust approach to defining the probability metrics. The organization using these metrics needs to document their approach. The model can be scaled from the circuit or system level to the facility level. It provides stakeholders with the ability to understand the effectiveness of their integrity resources. The level of subjectivity and accuracy is a function of how the model is implemented; and the frequency with which it is studied.

6 Conclusion

Corrosion of pressure equipment can have significant implications on assets, people, and the environment. Corrosion is a complicated subject and specific topics like microbially influenced corrosion present additional challenges as there is no consistent agreement between experts on the drivers. In many cases, degradation comes in a cocktail of forms. As such, locating and evaluating corrosion damage presents additional challenges for inspection and mitigation. The Impact Study by AMPP indicates that management struggles to understand the associated risk. The development of the dynamic corrosion risk model provides a mechanism to address this gap.

From the literature review it was concluded:

- Diagnosis of MIC requires chemical and process surveillance in addition to inspection and molecular microbiological methods.
- In austenitic stainless steels there is likely a synergistic effect between some forms of MIC and pitting corrosion.
- Currently, there is no practical way to physically distinguish between pitting and MIC.

The case study involving the MIC degraded test plate concluded that:

- MIC and/or pitting corrosion is difficult to inspect using any volumetric NDT methods.
- NDT methods and individual techniques need to be considered when performing corrosion monitoring. Where possible multiple NDT methods should be used.

- When performing FFS, higher PoD methods should be used to ensure FFS accuracy particularly when evaluating higher-risk applications.

The corrosion risk assessment model developed:

- Provides a link between the preventative and mitigative aspects of an integrity program.
- The corrosion risk assessment model demonstrates that chemical and molecular microbial methods in addition to inspection data reduce the risks associated with degradation.
- The corrosion risk assessment model can be adapted to the maturity of the integrity program.

This work has demonstrated the need to continue the research and development of surveillance tools (chemical, process, and inspection) to monitor the degradation of austenitic steels. Specifically, it is recommended that the following areas be considered for study in future works:

- Development of artificial intelligence and machine learning algorithms for ultrasonic and radiographic inspection tools to improve POD of localized corrosion, such as MIC.
- Continuing research into the chemical and electrical MIC processes associated with MIC to improve the understanding of the interaction of the various forms of MIC. This should improve the detection, monitoring, and sampling for MIC.

These tools will improve the understanding of MIC degradation and its responses. This will aid in the development of practical MIC models. As MIC models are refined, the undeveloped events can be refined and enhance the presented corrosion risk assessment model.

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