Table B.1: Carbon steel corrosion threat mechanisms and primary assurance strategies (continued)

Mechanism Not in parent EI document	Wear-out mode and type	Predictable	Value of periodic inspection (if guided correctly)		Primary management strategies
			Damage (cracking or wall loss)	Barrier performance	
INTERNAL					
Corrosion erosion (in nominally sand free systems)	Rate – wall loss gradual wear-out increasing with age but can be rapid	Experience only	MEDIUM as typically rates are lower though prone areas can be harder to define	Can be MEDIUM for inhibited or coated equipment but LOW for coated piping large systems and flanged joints	Sand removal Periodic inspection in some cases
Injection/mix point corrosion	Rate – wall loss gradual wear-out increasing with age	Experience only	HIGH as location-specific	HIGH – one-off surveys identifying quill presence and length	Design Periodic inspection
Amine corrosion	Rate – wall loss gradual wear-out increasing with age	Threshold parameters	MEDIUM similar to CO_2/H_2S corrosion but less predictable and highly location-specific	Typically, only CRA barriers used	KPI/IOW barrier monitoring Periodic inspection Operating controls
Amine cracking	Susceptibility – random cracking at all ages	Threshold parameters	LOW unless thoroughly inspected and future operating conditions remain within the historical operating envelope	HIGH – field hardness checks one-off survey can verify probability of failure	Design KPI/IOW barrier monitoring Operating controls
Glycol corrosion	Rate – wall loss gradual wear-out increasing with age	Threshold parameters	As per CO_2 corrosion, but this mechanism is typically low probability	N/A	KPI/IOW barrier monitoring Periodic inspection

Table B.1: Carbon steel corrosion threat mechanisms and primary assurance strategies (continued)

Mechanism Not in parent EI document	Wear-out mode and type	Predictable	Value of periodic inspection (if guided correctly)		Primary management strategies
			Damage (cracking or wall loss)	Barrier performance	
EXTERNAL (Atmospheric, partial or full immersion)					
CUI	Rate – wall loss gradual wear-out increasing with age	Models exist but they cannot predict the time spent water-wet and are conservative	HIGH	MEDIUM for visual inspection of cladding and persistent water sources LOW-MEDIUM for coating condition. Coatings are not reliable barriers – CUI involves trapped liquids unlike atmospheric exposure and at effective water traps paint coating can degrade within 1–2 years, TSA within 5 years under worst case conditions MEDIUM where stripping insulation and prevention of long-term wetting though reinsulation with poor QC can introduce threats	Periodic inspection
CUPS	Rate – wall loss gradual wear-out increasing with age	Rules of thumb exist	MEDIUM – access often poor no reliable NII methods. HIGH for equipment that can be isolated and has supports temporarily moved in outages or removed and replaced. MEDIUM for trunnion (internal) corrosion of process pipe (significant blind areas)	HIGH (pipe support types and design information collected from field) can help to reduce the PoF for example high welded doubler or wear plate thickness, welded status, sealed trunnion weep holes, clamped arrangements	Periodic inspection Not for process pipe exposed inside trunnions, barrier/design solutions should be the focus area as well as sample destructive inspection

Table B.1: Carbon steel corrosion threat mechanisms and primary assurance strategies (continued)

Mechanism Not in parent EI document	Wear-out mode and type	Predictable	Value of periodic inspection (if guided correctly)		Primary management strategies
			Damage (cracking or wall loss)	Barrier performance	
EXTERNAL (Atmospheric OR partial or full immersion)					
External atmospheric corrosion	Rate – wall loss gradual wear-out increasing with age	Rules of thumb exist	HIGH	HIGH (coating) – unlike CUI significant coating deterioration typically not between inspection periods	Periodic inspection
Underground corrosion	Rate – wall loss gradual wear-out increasing with age but can be rapid in the case of stray current corrosion	Rules of thumb exist but stray current corrosion is not predictable	MEDIUM where CP ineffective not high because of access/ excavation constraints and also due to potentially rapid stray current corrosion	MEDIUM (coating) where CP completely ineffective, typically local areas, not high because of access/excavation constraints, and due to potentially rapid stray current corrosion	KPI barrier monitoring (CP effective) Periodic inspection the only effective method for local wetted areas in very dry surrounding soil (or other recognised blind spots or long-term areas of no protection)
Seawater immersion corrosion	Rate – wall loss gradual wear-out increasing with age but can be rapid in the case of stray current corrosion	Rules of thumb exist but stray current corrosion is not predictable	HIGH for pipeline internal pigs but not in cases of stray current corrosion MEDIUM for any external inspection due to the intensive cleaning requirements, poor visibility and limitations of NUVs	MEDIUM (anode depletion visual)	KPI barrier monitoring Periodic inspection is effective for anode condition and pipeline pigging but less so for stray current effects

ANNEX C
CARBON STEEL CORROSION THREAT MORPHOLOGY AND MOST PROBABLE RELEASE SIZE

Morphology of corrosion damage, the shape and size of it, the expected surface topography it produces or the frequency of occurrence at depth, is an important feature that governs required inspection coverage and prone area definitions, CoF and interpretation of inspection data.

CTA morphology when combined with fitness-for-service and mechanical failure knowledge can help to identify particularly high safety risks. Table C.1 can be used to audit CS pressure systems equipment more vulnerable to rupture failures; it provides:

- a list of corrosion threat morphologies;
- a list of corrosion threat most likely release or hole sizes, and
- a list of threats in order of the potential to give rise to a rupture type failure and the circumstances that make rupture more likely to occur.

Table C.1: Carbon steel corrosion threat morphology and most probable release size

Mechanism	Wear-out mode	Morphology	Probable release size	Rupture more likely
CUI and also applies to CUI in penetrations	Rate	Widely variable depending on the efficiency of water hold up. CUI can produce semi or full immersion conditions depending on delivery, geometry hold up and exit of water. Transient wetting away from prone areas gives general mesa type corrosion but more permanent wetting can generate large areas of uniform corrosion e.g. penetrations with seals above and below	Corrosion hole – typical Rupture – High energy gas and NGL inventory Pressure >10 barg. Typically, PoF –2 compared with corrosion hole	Thicker pipe with significant overdue inspection or insufficient coverage and significant wall thinning and higher pressures (same PoF). Localised longitudinal continuous corrosion where MAWT can approximate that of general wall loss (–1 PoF) can cause unzipping. Higher temperature penetrations/ piping at height/equipment in dry areas where water delivery from attached piping is not obvious
CO_2 corrosion	Rate	Widely variable but typically not general. Semi localised mesa-type wall loss in flowing liquids. Requires high % surface area coverage to locate thinnest defects. Can be highly localised in welds or arranged in grooves along pipe in stratified lower velocity flow. Typically, local pitted areas at/ near welds in wet gas piping dead-legs	Corrosion hole – flowing liquids/int. coating holidays, circumferential weld corrosion Pinholes – gas systems where water condenses at welds or condensate collection piping at welds Rupture – not common for single phase gas systems. Possible in multiphase systems > 10 barg –2 PoF	Thicker pipe with overdue inspection or insufficient coverage and significant wall thinning and higher pressures (same PoF). In multiphase low flow liquids lines localised longitudinal groove corrosion where MAWT can approximate that of general wall loss (–1 PoF) can cause unzipping

Table C.1: Carbon steel corrosion threat morphology and most probable release size (continued)

Mechanism	Wear-out mode	Morphology	Probable release size	Rupture more likely
CUPS	Rate	Trunnion corrosion via water ingress through weep holes is a special case and can cause semi or full immersion conditions depending on delivery, weep hole location, etc.	As per CUI	As per CUI, possible for corrosion of pipe within large trunnions with full immersion history and no water egress route (–1 PoF)
External atmospheric corrosion	Rate	Localised concave wall loss under scabs or large areas of uneven general corrosion under scale	Typically, Pinhole or corrosion hole – for thin wall pipe for which there is most leak history	Not commonly encountered. Corrosion rates often sufficiently low and probability of detection sufficiently high to mitigate ongoing serious corrosion, most likely for aged, smaller diameter, HP uninspected piping at height or similar inaccessible locations, equipment unintentionally immersed
CUPS	Rate	Typically localised in pipe support crevices	Corrosion hole – as per CUI	Not commonly encountered, unlikely to produce the larger uniform areas of loss needed for rupture, may be possible in time
O_2 corrosion in waters	Rate	As per CO_2 corrosion for liquids	As per CO_2 corrosion for liquids	Groove corrosion and biofouling in pipeline 6 o'clock position prone to rupture/unzipping in HP Water Injection pipelines/tubing though low energy. Considered unlikely for topsides
Pure erosion	Susceptibility and rate	Sculpted, defined shape of loss relating to sand impact typically tapered depth	Corrosion hole – an initial large area typically tapers to a point	Rupture – not as common due to localised nature and tapering, exception could be HP gas lines (erosion not commonly encountered but possible, well start-up routes through small diameter pipe)

Table C.1: Carbon steel corrosion threat morphology and most probable release size (continued)

Mechanism	Wear-out mode	Morphology	Probable release size	Rupture more likely
Corrosion erosion	Rate	A mixture of CO_2 corrosion for liquids phase and erosion	A mixture of CO_2 corrosion for liquids phase and erosion	Not commonly encountered
MIC	Rate	Highly localised, multiple or isolated sharp deep pits	Corrosion hole – stagnant dead-legs	Not commonly encountered
H_2S driven corrosion	Rate	Adds highly localised pitting to CO_2 corrosion	Adds pinhole or corrosion hole to CO_2 corrosion	Can initiate cracking in extreme sour service but not typically encountered in North Sea
Amine corrosion	Rate	As per CO_2 corrosion for liquids phase but tends to be more localised and not vulnerable to grooving etc.	Corrosion hole	Not commonly encountered
SSCC	Susceptibility	Fine internal cracks initiating at welds or HAZ can progress in parent material	Fine cracks	Not commonly encountered, cracks progress through wall before long enough to initiate fast fracture. Can depend on metallurgy vulnerability and inventory
HIC	Rate	Step-wise, mid-wall, multiple fine cracks or blisters can appear on external surface too stress oriented (SOHIC)	Rare cause of failure, can be monitored over time	
Amine cracking	Susceptibility	As per H_2S SSCC		
Glycol corrosion	Rate	Not enough experience with corrosion and failures		
Underground corrosion	Susceptibility	Not enough experience with corrosion and failures		
Seawater immersion corrosion	Susceptibility	Not enough experience with corrosion and failures		

ANNEX D
CORROSION RESISTANT ALLOY CORROSION THREAT MECHANISMS AND PRIMARY ASSURANCE STRATEGIES

It is helpful to document a list of the threats to be considered in CTA. Not all threats are suited to the same risk management strategy, typically primarily as a result of the wear-out mode and predictability. Table D.1 contains:

- A list of corrosion threats as a minimum to be considered in CTA for CRAs (austenitic and duplex grades). Only the most common CRAs are considered.
- Columns for threat wear-out mode, predictability, value of inspection (for the damage and for barriers) and, based upon these, primary risk management strategies.

Low value inspection is defined as where it is impractical to inspect sufficiently frequently to anticipate or pre-empt random failure modes and/or involves a combination of obvious, as of yet unresolved, access or technology restrictions.

High value inspection is typically that which has a proven track record to pre-empt failure, providing the correct choice of coverage, technique, prone area definition and interval is provided to deliver personnel to the right place at the right time.

Note: geometry-defined threats do not often demand different PoF criteria as such and therefore are often adequately managed as part of each corrosion mechanism assessment by reviewing whether they represent a significantly higher PoF than the bulk. In some cases, they may all be reviewed in a dedicated register together in order to find the highest priorities.

Basic threat types were selected according to prevalence and typical bulk topsides and non-flexible pipelines materials selection as shown in Figure 7. However, the same principles which are required to characterise threats will relate to all materials that are vulnerable to corrosion.

Table D.1: Corrosion resistant alloy corrosion threat mechanisms and primary assurance strategies

Mechanism Not in parent EI document	Wear-out mode and type	Predictable	Value of periodic inspection (if guided correctly)		Primary management strategies
			Damage (cracking or wall loss)	Barrier performance	
INTERNAL					
SSCC closely linked to internal chloride stress cracking (CSC) in the presence of H_2S	Susceptibility – random cracking at all ages	Threshold parameters and experience	Compliant with NACE MR0175/ ISO15156 N/A but note there are safe operating window parameters see below: Not compliant with NACE MR0175/ISO15156 either not manufactured for sour service or designed for sour service but operating outwith safe operating windows. MEDIUM for vessels (cracks initiate internally, access possible, thick walled less aggressive environments, charging profiles can arrest cracks, unlikely to pre-empt failure but cracks can be detected) – but only if future operating conditions remain within historical (>2 yrs. at each severity) operating envelope LOW for pipe/pipelines – no access or known reliable pigging methods	LOW or N/A (hardness checks) – this can provide some assurance for some grades but there are more important compositional and environmental parameters combined with the ability of local conditions/weld profile geometry to concentrate chlorides which are key to threshold parameters. If the CRA is a barrier as vessel cladding or overlay, then cracking is N/A for itself though it could be for the substrate (hardness controls may be relaxed for clad carbon steel) and there is HIGH inspection value for early internal inspection of fabrication crack defects in cladding	KPI/IOW barrier monitoring Laboratory testing to further verify asset-specific combinations of environmental threshold parameters The KPI limits in ISO15156 for CRAs can be conservative but adequate data are not available to modify them unless appropriate testing is conducted to represent the particular combination of parameters in service Many operators fund their own testing. Caveat – the ISO limits are for parent material not welds which can be more vulnerable Periodic inspection if CRA is a barrier cladding for welded carbon steel vessels or equipment

Table D.1: Corrosion resistant alloy corrosion threat mechanisms and primary assurance strategies (continued)

Mechanism Not in parent EI document	Wear-out mode and type	Predictable	Value of periodic inspection (if guided correctly)		Primary management strategies
			Damage (cracking or wall loss)	Barrier performance	
INTERNAL					
MIC	Rate – wall loss gradual wear-out increasing with age	Experience only	MEDIUM though CRAs can be less vulnerable than carbon steel	N/A	KPI/IOW barrier monitoring Identification of long-term large process dead-legs Periodic inspection Operating controls i.e. regular flushing with fluids to disperse chemicals (biocide and inhibitor)
Pure erosion Note: Refer to EI *Guidelines on sand erosion and erosion-corrosion management*, 1st edition	As per carbon steel	As per carbon steel	As per carbon steel	N/A	As per carbon steel
Chloride stress corrosion cracking of stainless steel in concentrated production environments (not sour)	Susceptibility – random cracking at all ages	Threshold parameters (though not all able to be reliably assessed) and experience	LOW on account of the typically low probability, driven if local conditions accumulate to become more aggressive than bulk and when triggered, time to failure can proceed rapidly. Additionally, no techniques to reliably detect internal fine cracks externally	N/A for CRA equipment If the CRA is a barrier as vessel cladding or overlay to protect carbon steel, then cracking is N/A but corrosion could be an issue for a carbon steel substrate so there is HIGH inspection value for early internal inspection of fabrication defects in cladding	KPI/IOW barrier monitoring Design (Typically, will still require inspection to protect a substrate if CRA is in the form of cladding due to fabrication defects)

Table D.1: Corrosion resistant alloy corrosion threat mechanisms and primary assurance strategies (continued)

Mechanism Not in parent EI document	Wear-out mode and type	Predictable	Value of periodic inspection (if guided correctly)		Primary management strategies
			Damage (cracking or wall loss)	Barrier performance	
Pitting and crevice corrosion of stainless steel in production environments	Not enough experience	Not enough experience	LOW typically not responsible for failures in upstream operations, but pitting is too small to detect with NII. MEDIUM for vessel internal inspection	N/A for CRA equipment HIGH inspection value if the CRA material is present as a barrier i.e. vessel cladding or overlay for early internal inspection of fabrication crack defects in cladding and periodic checks for pitting	KPI/IOW barrier monitoring Design (Typically, will still require inspection to protect a substrate if CRA is in the form of cladding)
O_2 corrosion (SCC and pitting) in Waters	Susceptibility – random cracking or pitting at all ages, can accelerate after periods of stagnation due to formation of deposit/crevices	Threshold parameters and experience	LOW the corrosion pits can be too small to detect with NII and can progress rapidly to failure; once initiated, the locations where crevices form are not easy to anticipate. Includes CRA flanges not weld-overlaid. MEDIUM for vessel internal visual	N/A	KPI/IOW barrier monitoring Design Operating controls Inspection may be of some value where internal visual possible (typically vessels)