ASSESSMENT AND REHABILITATION OF CORROSION UNDER PIPE SUPPORTS (CUPS): DEVELOPMENT AND VALIDATION OF A STRUCTURED INTEGRITY DECISION MODEL

Pragash Krishnasamy

Abstract

Corrosion Under Pipe Supports (CUPS) remains a persistent degradation mechanism in offshore piping systems, frequently resulting in severe localised wall loss and structural uncertainty. This study presents a Structured CUPS Integrity Decision Model (SCIDM) integrating inspection data, damage mechanism identification, structural thickness verification, Fitness for Service (FFS) assessment, reduced allowable pressure evaluation (MAWPr), rehabilitation engineering, and recurrence elimination within a deterministic governance framework. A field case involving carbon steel process piping revealed 75.6% wall loss, with a minimum measured thickness of 2.0 mm compared to a required structural thickness of 2.8 mm. API 579-1 Part 5 Level 2 assessment yielded a Remaining Strength Factor (RSF) of 0.9457, satisfying geometric collapse acceptance criteria. However, the reduced Maximum Allowable Working Pressure (MAWPr) determined using the reference stress methodology was 52.10 psig, significantly below the operating pressure of 145.033 psig and design pressure of 256.708 psig. Projection of corrosion progression produced negative MAWPr values, mathematically signifying complete loss of residual pressure containment capacity within the allowable stress framework.The case demonstrates that structural incapacity must be verified through MAWPr-based pressure capacity evaluation rather than corrosion rate extrapolation alone. Permanent rehabilitation using a Full Encirclement Type B sleeve designed in accordance with ASME PCC-2 restored full design pressure capability through an independent load transfer mechanism, while thermoplastic I-Rod support redesign eliminated the root cause of crevice formation. The SCIDM framework formalises deterministic cross-standard integration into a reproducible structural governance model for offshore asset integrity management and establishes a robust baseline for reliability-based future research.

Keywords:
Corrosion Under Pipe Support (CUPS), Offshore process piping, Fitness for Service (FFS), MAWP, Rehabilitation, Asset integrity

Received: *26 August, 2025*
Revised: *30 May, 2026*
Accepted: *15 June, 2026*
Published: *30 July, 2026*

NGL Tech Sdn. Bhd. Suite 8-3A, Wisma UOA 2, Jalan Pinang, Kuala Lumpur, 50450 Kuala Lumpur, Federal Territory of Kuala Lumpur.

Corresponding author:
pragash.krishnasamy@gmail.com

DOI: *https://doi.org/10.54552/9b7tkz23*

List of Notations:

CA = Corrosion allowance (mm)
CR = Corrosion rate (mm/year)
CR_{cap} = Capacity ratio (dimensionless)
D_o = Outside diameter of pipe (mm)
D_i = Inside diameter of pipe (mm)
D_s = Outside diameter of sleeve (mm)
E = Longitudinal weld joint efficiency (pipe)
E_s = Weld joint efficiency (sleeve)
FCA = Future corrosion allowance (mm)
L = Length of local metal loss (mm)
$MAWP$ = Maximum Allowable Working Pressure (psig)
$MAWPr$ = Reduced Maximum Allowable Working Pressure (psig)
P_{design} = Design pressure (psig)
$P_{operating}$ = Operating pressure (psig)
RL = Remaining life (years)
RSF = Remaining Strength Factor
RSF_a = Allowable Remaining Strength Factor (0.9)
S = Allowable stress at design temperature (MPa)
S_s = Allowable stress for sleeve material (MPa)
t = Wall thickness (mm)
t_{actual} = Measured minimum wall thickness (mm)
$t_{nominal}$ = Nominal original wall thickness (mm)
t_{req} = Required structural minimum thickness (mm)
$t_{structural}$ = Structural minimum thickness per API 574 (mm)
$t_{pressure}$ = Pressure design thickness per ASME B31.3 (mm)
t_{MA} = Minimum Alert Thickness (mm)
t_{sleeve} = Required sleeve thickness (mm)
Y = ASME B31.3 pressure design coefficient
σ_{hoop} = Hoop stress (MPa)
Δt = Time interval between inspections (years)
$Fe \rightarrow Fe^{2+} + 2e^-$ = Anodic dissolution reaction
$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$ = Cathodic oxygen reduction reaction

1.0 INTRODUCTION

Corrosion Under Pipe Supports (CUPS) remains one of the most challenging degradation mechanisms in offshore facilities due to concealed crevice geometries beneath support shoes. Differential aeration, chloride accumulation, and coating degradation accelerate localised metal loss. Literature on CUPS and integrity management can be grouped into four domains:

- Damage Mechanisms and Crevice Corrosion Behaviour – Accelerated anodic dissolution in shielded crevices (Costa *et al.,* 2022; Li *et al.,* 2022).
- Fitness for Service Methodology – RSF-based plastic collapse assessment distinguishing maintenance criteria from design criteria. (Takuyo KAIDA; 2009)
- Rehabilitation Engineering – ASME PCC-2 formalisation of permanent sleeve repair methodologies capable of independent pressure containment. (M.D Chapetti a, J.L Otegui a, C Manfredi a, C.F Martins b; 2001)
- Integrity Governance and Digitalisation (2018–2025) – Increasing emphasis on probabilistic corrosion modelling and digital inspection integration (Melchers, 2021; Wang *et al.,* 2024).

However, deterministic integration of inspection, FFS assessment, MAWP recalculation, rehabilitation engineering, and recurrence elimination into a unified workflow remains under structured. The objective is to develop and validate a deterministic Structured CUPS Integrity Decision Model integrating inspection, structural verification, FFS assessment, rehabilitation engineering, and preventive redesign.

2.0 GOVERNING EQUATIONS AND STANDARDS FRAMEWORK

This section defines the deterministic engineering criteria forming the foundation of the Structured CUPS Integrity Decision Model (SCIDM). The framework integrates ASME B31.3, API 570, API 574 and API 579-1 into a unified structural verification methodology.

2.1 Minimum Pressure Design Thickness (ASME B31.3)

The minimum required thickness to resist internal pressure is calculated using the allowable stress formulation:

$$t_{pressure} = \frac{PD_o}{2(SE + PY)} \quad \text{(Eq.1)}$$

For the present case:
Design Pressure = 256.708 psig
Operating Pressure = 145.033 psig
Calculated:
$t_{pressure,design} = 1.40$ mm
$t_{pressure,design} = 0.79$ mm
These values represent pressure containment thickness only and do not account for structural loading.

2.2 Structural Minimum Thickness (API 574)

Where $t_{structural}$ accounts for external loads, support stresses, and bending effects.

The governing required thickness is:
$t_{req} = \max(t_{pressure}, t_{structural})$ (Eq.2)
For the present case: $t_{structural} = 2.8$ mm
Thus: $t_{req} = 2.8$ mm
Structural inadequacy exists when: $t_{actual} < t_{req}$

2.3 Minimum Thickness

Minimum Alert Thickness (API 574): $t_{MA} = 3.3$ mm
Corrosion Allowance (Design Basis): $CA = 3.0$ mm
Design minimum thickness including corrosion allowance:
$t_{min,design} = t_{req} + CA$ (Eq.3)
Calculated: $t_{min,design} = 5.8$ mm
This represents the design basis thickness and is distinct from the structural screening thickness t_{req}.
Mill tolerance limits (informational per API 574):
Maximum: +2.38 mm
Minimum: −0.79 mm
These tolerances do not alter structural adequacy evaluation.

2.4 Remaining Strength Factor (API 579-1 Part 5 Level 2)

For Level 2 assessment under API 579-1 Part 5, RSF is determined using the reference stress methodology for local metal loss.

$$RSF = \frac{Collapse\ strength\ of\ damaged\ component}{Collapse\ strength\ of\ undamaged\ component} \quad \text{(Eq.4)}$$

Acceptance criterion: $RSF \geq 0.9$ (Eq.5)
RSF is determined using the reference stress methodology incorporating:
- Critical Thickness Profile (CTP)
- Flaw length interaction (Folias factor)
- Reduced collapse strength

RSF evaluates geometric acceptability of the flaw configuration but does not alone confirm pressure containment capability.

2.5 Recalculated MAWP (API 579-1 Part 5 Level 2)

For components containing local metal loss, pressure containment capability must be evaluated using the reduced strength methodology of API 579-1 Part 5. The undamaged code-based Maximum Allowable Working Pressure (MAWP) is determined in accordance with ASME B31.3. For the damaged component, the Reduced Maximum Allowable Working Pressure (MAWPr) is calculated using:
$MAWPr = RSF \times MAWP_{undamaged}$ (Eq.6)
Structural adequacy for continued service requires:
$MAWPr \geq P_{operating}$ (Eq.7)
When: $MAWPr \geq P_{operating}$
the component does not possess adequate pressure containment capability under the allowable stress framework. In this study, MAWPr values are obtained directly from the API 579-1 Part 5 Level 2 assessment output.

2.6 Wall Loss

Percentage wall loss relative to nominal thickness is defined as:

$$\%WL = \frac{t_{nominal} - t_{actual}}{t_{nominal}} \times 100 \quad \text{(Eq.8)}$$

For the present case: $\%WL = 75.6\%$

2.7 Corrosion Rate and Remaining Life (API 570)

Long-Term Corrosion Rate:

$$CR_{LT} = \frac{t_{initial} - t_{actual}}{\Delta t} \quad \text{(Eq.9)}$$

Short-Term Corrosion Rate:

$$CR_{ST} = \frac{t_{previous} - t_{actual}}{\Delta t} \quad \text{(Eq.10)}$$

The governing corrosion rate is:
$CR_{governing} = \max(CR_{LT}, CR_{ST})$ (Eq.11)

Remaining Life:

$$RL = \frac{t_{actual} - t_{req}}{CR_{governing}} \quad \text{(Eq.12)}$$

When: $t_{actual} < t_{req}$ (Eq.13)
the component no longer satisfies minimum structural thickness requirements, and structural inadequacy governs irrespective of projected remaining life.

3.0 METHODOLOGY – STRUCTURED CUPS INTEGRITY DECISION MODEL (SCIDM)

The SCIDM comprises seven deterministic stages:

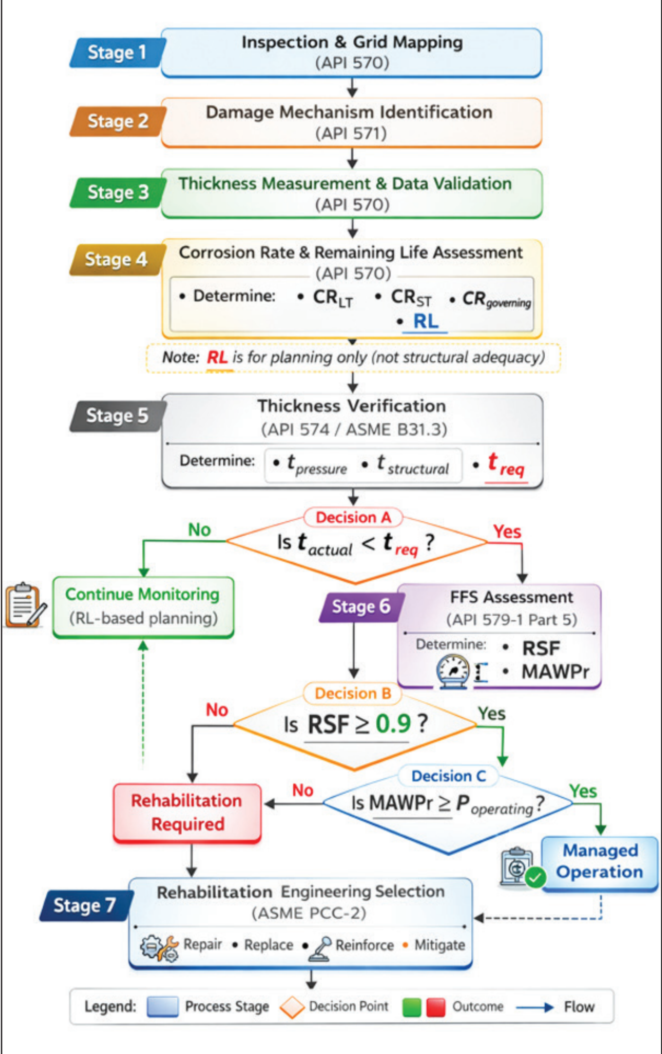

Figure 1: SCIDM deterministic workflow architecture

4.0 DAMAGE MECHANISM, FAILURE MECHANISM AND FAILURE MODES

Corrosion Under Pipe Supports (CUPS) is initiated by electrochemical processes but results in structural failure when wall thickness reduction compromises pressure containment.

This section distinguishes clearly between:

- Damage mechanism – the corrosion process
- Failure mechanism – the structural response
- Failure mode – the physical outcome

4.1 Damage Mechanism

CUPS is classified under external corrosion in API 571. It occurs due to crevice confinement beneath pipe supports where moisture and chlorides accumulate. The primary electrochemical reactions are:

Anodic dissolution: $Fe \rightarrow Fe^{2+} + 2e^{-}$ (Eq.14)

Cathodic oxygen reduction:

$O_2 + 2H_2O + 4e^{-} \rightarrow 4OH^{-}$ (Eq.15)

Restricted oxygen access inside the crevice creates an anodic region beneath the support, accelerating localised metal loss.

This results in Local wall thinning, Pitting within confined regions or Progressive reduction in cross-sectional area.

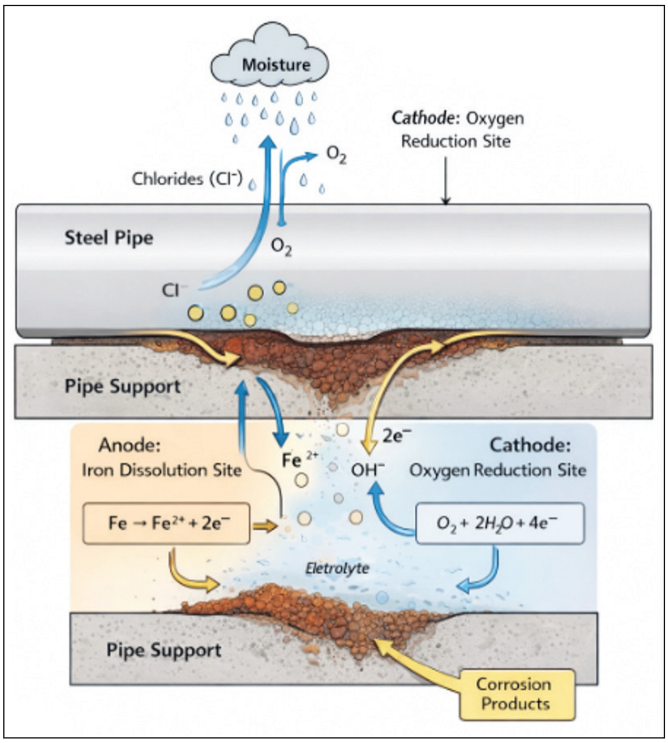

Figure 2: CUPS crevice corrosion mechanism

4.2 Failure Mechanism

Structural failure occurs when section loss increases stress beyond allowable limits.

For internal pressure, the governing hoop stress is:

$$\sigma_{hoop} = \frac{PD_o}{2t} \quad \text{(Eq.16)}$$

As wall thickness decreases, hoop stress increases. When hoop stress exceeds allowable stress, plastic collapse may occur. Thus, the structural failure mechanism is:

Local wall thinning → Stress amplification → Reduced pressure capacity → Collapse.

4.3 Failure Modes

The observable failure mode depends on severity of wall loss.

Table 1: Damage mechanism, failure mechanism and failure modes for CUPS

Damage Mechanism	Structural Failure Mechanism	Failure Mode
Crevice corrosion	Localised wall thinning	Leak
Accelerated pitting	Stress concentration	Pin hole leak
Progressive section loss	Reduced hoop strength	Through wall leak
Severe local thinning	Plastic collapse under pressure	Rupture
Extended wall loss at support	Reduced bending stiffness	Sagging

5.0 CASE STUDY APPLICATION

5.1 Inspection Findings and Thickness Evaluation

Field inspection identified severe localised corrosion beneath the pipe support consistent with Corrosion Under Pipe Support

(CUPS). Grid based pit gauge and ultrasonic thickness measurements confirmed:

- Nominal wall thickness, $t_{nominal} = 8.18$mm
- Minimum measured thickness, $t_{actual} = 2.0$mm

Percentage wall loss:

$$\%WL = \frac{8.18 - 2.0}{8.18} \times 100 = 75.6\% \quad \text{(Eq.8)}$$

The magnitude of wall loss confirms advanced local metal loss within the support region.

5.2 Structural Minimum Thickness Verification

Minimum required thickness for structural adequacy was determined in accordance with ASME B31.3 and API 574 requirements.

Required minimum thickness: $t_{req} = 2.8$mm

Comparison: $t_{actual} = 2.0\,\text{mm} < t_{req} = 2.8\,\text{mm}$ (Eq.13)

the component does not satisfy minimum structural thickness requirements. However, thickness screening alone does not determine pressure containment capability when localised metal loss is present. Therefore, a Fitness-for-Service (FFS) assessment was performed.

5.3 Fitness-for-Service Assessment (API 579-1 Part 5 Level 2)

A Level 2 assessment for local metal loss (Type A component) was performed in accordance with API 579-1 Part 5.

The evaluation incorporated:

- Critical Thickness Profile (CTP)
- Flaw length interaction (Folias factor correction)
- Reduced collapse strength determination

The calculated Remaining Strength Factor (RSF) was:

$RSF = 0.9457$

The Level 2 acceptance criterion requires:

$RSF \geq 0.9$ (Eq.5)

Since: $0.9457 \geq 0.9$

the flaw geometry satisfies the Level 2 geometric collapse acceptance requirement. However, it is important to emphasise that RSF evaluates geometric acceptability of the flaw configuration only. Compliance with the RSF acceptance criterion does not confirm adequate pressure containment capability. In accordance with Section 2.5, pressure capacity of the damaged component must be independently verified through evaluation of the Reduced Maximum Allowable Working Pressure (MAWPr). Therefore, although the geometric screening criterion is satisfied, the governing structural decision requires assessment of MAWPr relative to the operating pressure.

5.4 Reduced Maximum Allowable Working Pressure (MAWPr)

Following determination of RSF in Section 5.3, the pressure containment capability of the damaged component was evaluated using the Reduced Maximum Allowable Working Pressure (MAWPr) derived from the API 579-1 Part 5 Level 2 assessment. At the measured thickness of 2.0 mm, the FFS assessment produced:

$MAWPr = 52.10$ psig

For comparison:

Design Pressure = 256.708 psig

Operating Pressure = 145.033 psig

Since: $MAWPr < P_{operating}$ (Eq.7)

the corroded piping segment does not satisfy the allowable pressure containment requirement for continued operation under existing conditions.

It is important to note that although the Remaining Strength Factor satisfied the geometric acceptance criterion (RSF ≥ 0.9), this does not ensure adequate pressure containment. The governing serviceability criterion is the comparison between MAWPr and operating pressure in accordance with Section 2.5. The relationship between remaining wall thickness and MAWPr obtained from the Level 2 assessment is summarised in Table 2.

Table 2: Reduced maximum allowable working pressure (MAWPr) versus remaining wall thickness (API 579-1 Level 2)

Condition	Remaining Thickness (mm)	RSF	MAWPr (psig)	Comparison vs Operating Pressure
Nominal Condition	8.18	1.000	Code MAWP	> P_operating
Structural Minimum	2.80	0.9457	87.4	< P_operating
Measured Condition	2.00	0.9457	52.1	< P_operating
Projected Degradation	1.50	0.9457	20.5	< P_operating
Critical Condition	1.00	0.9457	Negative	No allowable capacity

The RSF value shown corresponds to the governing local metal loss region evaluated under the Level 2 reference stress methodology. The progressive reduction in MAWPr demonstrates that pressure containment capability deteriorates rapidly once wall thickness falls below the structural screening thickness. The deterministic comparison between MAWPr and operating pressure provides direct confirmation of structural inadequacy independent of corrosion rate projection.

5.5 Interpretation of Negative MAWPr

The reduced Maximum Allowable Working Pressure (MAWPr) obtained from the Level 2 assessment represents the allowable pressure capacity of the damaged component after accounting for geometric weakening through the Remaining Strength Factor (RSF).

In the present case:

$MAWPr = 52.10$ psig

$P_{operating} = 145.033$ psig

Since: $MAWPr < P_{operating}$ (Eq.7)

the component does not possess adequate pressure containment capability within the allowable stress framework.

It is critical to distinguish between geometric acceptability and pressure containment adequacy. Although the RSF value satisfied the Level 2 geometric screening criterion (RSF ≥ 0.9), the reduced allowable pressure capacity remains significantly below the operating pressure. This confirms that geometric collapse screening alone is insufficient for serviceability determination. The governing structural decision therefore rests on MAWPr evaluation rather than RSF acceptance alone.

5.6 Engineering Decision

The structural decision was based on deterministic criteria defined in Section 2:

$$t_{actual} < t_{req} \quad \text{(Eq.13)}$$

$$RSF \geq 0.9 \quad \text{(Eq.5)}$$

$$MAWPr < P_{operating} \quad \text{(Eq.7)}$$

Although the flaw geometry satisfied Level 2 acceptance requirements, the reduced allowable pressure capacity did not meet operating conditions. Accordingly, the piping segment did not satisfy API 570 requirements for continued service. Permanent rehabilitation was therefore required. This decision was governed by pressure capacity inadequacy rather than corrosion rate projection or geometric screening alone, reinforcing the deterministic hierarchy embedded within the SCIDM framework.

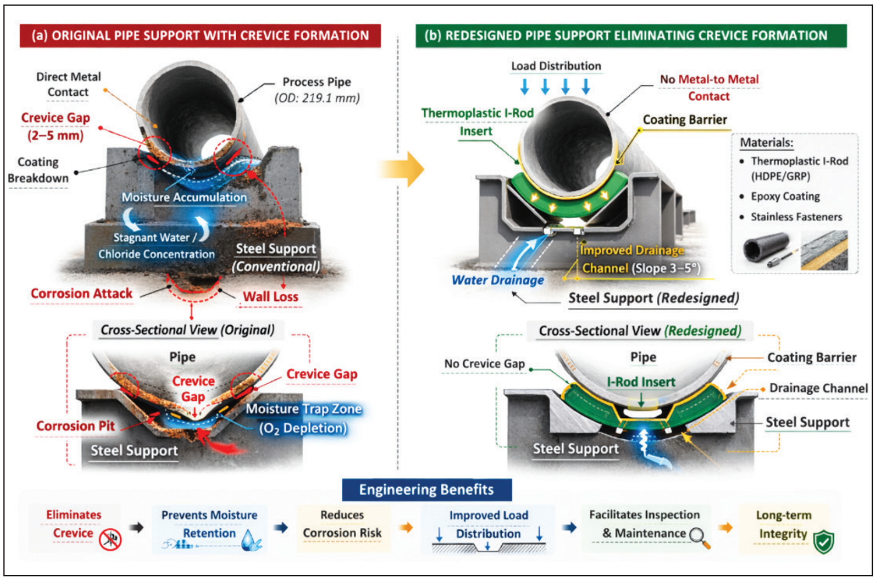

Figure 4: Comparison of conventional pipe support and redesigned I-rod support eliminating crevice formation

6.0 REHABILITATION ENGINEERING

6.1 Repair Options Evaluation

Table 3: Recalculated MAWP and capacity ratio

Repair Method	Code Reference	Permanent	Pressure Capacity	Selected
Composite Wrap	ASME PCC-2 Article 401	Conditional	Limited	No
Clamp	API 570	Temporary	Limited	No
Type B Sleeve	ASME PCC-2 Article 206	Yes	Full Design Pressure	Yes

6.2 Full Encirclement Type B Sleeve Design

Design considerations:

- Sleeve independently designed for full design pressure
- Full penetration longitudinal weld
- Circumferential welds transfer longitudinal load
- Joint efficiency 0.45 conservatively applied
- Thermal expansion and fatigue considered
- Material compatibility verified

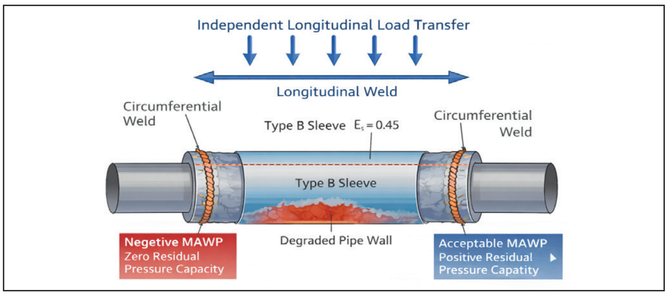

Figure 3: Type B sleeve load transfer concept

The Full Encirclement Type B sleeve was designed in accordance with the requirements of ASME PCC-2 Article 206. In accordance with this provision, the sleeve must be capable of independently sustaining the full internal design pressure without reliance on the remaining thickness of the degraded pipe wall. The required sleeve pressure thickness was determined using the ASME B31.3 allowable stress formulation for cylindrical pressure design:

$$t_{sleeve} = \frac{PD_s + 1}{2(S_s E_s + PY)} + CA \quad \text{(Eq.17)}$$

This formulation ensures that the sleeve alone satisfies pressure containment requirements under allowable stress criteria. By restoring pressure capacity through an independent load path, the Type B sleeve eliminates dependence on the locally thinned pipe section and satisfies the permanent repair intent of ASME PCC-2. Sleeve provides independent load path.

7.0 PREVENTION AND RECURRENCE ELIMINATION

Thermoplastic I-Rods eliminate crevice geometry and moisture retention.

- Eliminate crevice geometry
- Prevent moisture entrapment
- Improve drainage
- Reduce coating breakdown

Support redesign removes root cause of CUPS.

8.0 UNCERTAINTY AND SENSITIVITY

8.1 Measurement Uncertainty Assessment

Thickness measurements were obtained using NDT techniques in accordance with API 570 inspection practices. A conservative measurement tolerance of ±0.1 mm was considered to evaluate sensitivity of structural conclusions.

Measured thickness: $t_{actual} = 2.0$ mm
Upper bound: $t_{upper} = 2.1$ mm
Lower bound: $t_{lower} = 1.9$ mm

Recalculation of MAWPr under these bounds indicates that allowable pressure capacity remains significantly below the operating pressure in both cases.

Therefore, the conclusion of structural inadequacy is robust within realistic measurement uncertainty limits. The structural decision is not sensitive to minor thickness measurement variation. This confirms that the requirement for rehabilitation is structurally robust and not influenced by minor thickness measurement variation.

8.2 Sensitivity of Structural Capacity to Thickness Reduction

Although the reduced allowable pressure (MAWPr) values in this study were obtained directly from the API 579-1 Part 5 Level 2 assessment, the underlying structural sensitivity remains governed by the allowable stress formulation for internally pressurised cylindrical components. From the ASME B31.3 pressure design relationship introduced in Section 2.1, the Maximum Allowable Working Pressure (MAWP) for an undamaged component may be expressed as:

$$\text{MAWP} \propto = \frac{2SEt}{D - 2Yt} \quad \text{(Eq.18)}$$

This relationship indicates that allowable pressure capacity is proportional to wall thickness and inversely related to the geometric term ($D - 2Yt$). In simplified proportional form:

$$\text{MAWP} \propto = \frac{t}{D - 2Yt} \quad \text{(Eq.19)}$$

As wall thickness decreases due to corrosion, the numerator reduces linearly while the denominator simultaneously reduces through the geometric interaction term. This produces a nonlinear reduction in allowable pressure capacity. For damaged components evaluated under API 579-1 Part 5, the reduced allowable pressure is defined as:

$$MAWPr = RSF \times MAWP_{undamaged} \quad \text{(Eq.6)}$$

Thus, degradation in wall thickness reduces both:

- geometric collapse strength (through RSF), and
- allowable stress-based pressure capacity (through MAWP).

In the present case:

- 75.6% wall loss exists,
- $t_{actual} < t_{req}$,
- $\text{MAWPr} < P_{operating}$.

This confirms that the component is operating within a region of elevated structural sensitivity, where small additional reductions in thickness would result in disproportionately large reductions in allowable pressure capacity. Accordingly, deterministic capacity verification using MAWPr is essential when severe localised corrosion exists. Reliance on corrosion rate extrapolation alone would not adequately capture this nonlinear degradation of structural capacity.

9.0 DISCUSSION

9.1 Deterministic Structural Governance versus Corrosion Rate Extrapolation

Conventional integrity management practice frequently relies on corrosion rate projection and remaining life estimation as primary decision tools. While appropriate for uniform wall thinning, such approaches may be insufficient when severe localised corrosion mechanisms such as CUPS are present. Corrosion rate projection evaluates future degradation, whereas structural adequacy must be evaluated based on present capacity. Within the SCIDM framework, structural incapacity is triggered when any of the following deterministic conditions are satisfied:

$$t_{actual} < t_{req} \quad \text{(Eq.13)}$$

$$MAWPr < P_{operating} \quad \text{(Eq.7)}$$

These checks evaluate actual pressure containment capability rather than projected degradation trends. In the present case, remaining life calculations alone could not ensure structural adequacy. Although corrosion progression could be projected, the component already lacked sufficient allowable pressure capacity under current operating conditions. This demonstrates the limitation of corrosion rate extrapolation as a sole decision criterion in cases of severe local metal loss.

9.2 Interpretation of Reduced and Negative MAWP within Plastic Collapse Framework

The Reduced Maximum Allowable Working Pressure (MAWPr) determined in this study represents the allowable pressure capacity of the damaged component under the reference stress methodology of API 579-1 Part 5. The Remaining Strength Factor (RSF) reflects the ratio of collapse strength between damaged and undamaged configurations:

$$RSF = \frac{Collapse\ strength\ of\ damaged\ component}{Collapse\ strength\ of\ undamaged\ component} \quad \text{(Eq.4)}$$

The reduced allowable pressure is therefore:

$$MAWPr = RSF \times MAWP_{undamaged} \quad \text{(Eq.6)}$$

Although RSF satisfied the geometric acceptance criterion (RSF ≥ 0.9), the resulting MAWPr remained significantly below the operating pressure.

This distinction is fundamental:

- RSF evaluates geometric collapse acceptability
- MAWPr evaluates pressure containment capability

Structural adequacy requires satisfaction of both geometric and pressure capacity criteria. The present case demonstrates that geometric compliance does not necessarily imply pressure adequacy. The deterministic comparison between MAWPr and operating pressure provides a transparent and defensible engineering basis for intervention.

9.3 Cross Standard Integration and Governance Maturity

A significant contribution of this study is the structured integration of:

- API 570 – Inspection and corrosion rate
- API 571 – Damage mechanism classification
- API 574 – Structural minimum thickness
- API 579-1 – Fitness-for-Service assessment
- ASME B31.3 – Pressure design basis
- ASME PCC-2 – Permanent repair methodology

In conventional practice, these standards are frequently applied in isolation. The SCIDM framework consolidates them into a deterministic decision hierarchy, improving traceability and reducing practitioner variability. In offshore environments, where safety-critical service conditions exist, such integration strengthens regulatory defensibility and enhances engineering transparency.

10.0 LIMITATIONS AND FUTURE RESEARCH

10.1 Study Limitations

Although the Structured CUPS Integrity Decision Model (SCIDM) provides a deterministic and reproducible framework for managing severe localised corrosion, the present study is subject to the following limitations:

1. **Single Case Field Validation.** The framework was validated using one offshore gas process piping segment exhibiting severe CUPS. While the case represents a realistic high risk scenario, broader application across different pipe diameters, materials, operating pressures, and support configurations would strengthen generalisability.
2. **Deterministic Structural Assessment.** The methodology adopts deterministic equations based on allowable stress criteria and plastic collapse screening. Variability in material properties, corrosion morphology, and measurement uncertainty was evaluated through bounded tolerance analysis rather than probabilistic modelling.
3. **Local Metal Loss Idealisation.** The Level 2 FFS assessment assumes simplified local metal loss geometry consistent with API 579 screening procedures. Highly irregular pit morphology or complex multi-axial stress interaction was not evaluated using finite element modelling.
4. **Fatigue and Cyclic Loading Interaction.** While thermal expansion and load transfer were considered qualitatively in rehabilitation design, explicit fracture mechanics or fatigue crack growth analysis under cyclic pressure loading was not performed.
5. **Post Repair Long Term Monitoring.** The long-term performance of the Type B sleeve under extended service conditions was not analysed within this study. Longitudinal inspection data following repair would provide valuable validation of structural durability.

These limitations do not invalidate the deterministic conclusions of structural incapacity but define the boundary conditions of applicability.

10.2 Future Research Direction

The SCIDM framework establishes a deterministic baseline for structural governance. Future research will extend this model toward reliability based and predictive integrity management.

1. **Probabilistic Remaining Strength Factor Modelling.** Transition from deterministic RSF thresholds to stochastic RSF distributions incorporating thickness variability and material uncertainty.
2. **Bayesian Corrosion Rate Updating.** Integration of sequential inspection data using Bayesian inference to dynamically update corrosion growth rates and reduce uncertainty in remaining life estimation.
3. **Finite Element-Based MAWP Uncertainty Propagation.** Development of FEM based parametric models to quantify structural response under irregular metal loss geometry and propagate uncertainty through MAWP calculations.
4. **AI-Assisted Inspection Prioritisation.** Application of machine learning algorithms to classify support configurations and predict high risk CUPS locations across large asset networks.
5. **Digital Twin Integration.** Linking SCIDM decision logic with digital asset management systems to create real-time structural health governance dashboards.
6. **Structural Reliability Index Development.** Formulation of reliability indices (β) for corroded piping systems to align deterministic FFS outcomes with probabilistic risk-based inspection (RBI) frameworks.

10.3 Strategic Research Trajectory

The deterministic SCIDM architecture developed in this study provides the structural foundation upon which probabilistic, AI-driven, and digital twin-integrated integrity governance systems can be built. The progression from deterministic verification toward predictive asset intelligence represents a natural future research pathway.

11.0 CONCLUSION

This study developed and validated a Structured CUPS Integrity Decision Model (SCIDM) integrating inspection, structural verification, Fitness-for-Service assessment, reduced allowable pressure evaluation (MAWPr), rehabilitation engineering, and recurrence elimination within a deterministic governance framework. The field case demonstrated severe localised degradation with 75.6% wall loss and a minimum measured thickness of 2.0 mm compared to a required structural thickness of 2.8 mm. API 579-1 Part 5 Level 2 assessment produced:

- RSF = 0.9457
- MAWPr = 52.10 psig

Although the geometric collapse criterion was satisfied (RSF $\geq$ 0.9), the reduced allowable pressure capacity was significantly below the operating pressure of 145.033 psig. This confirmed structural inadequacy under current service conditions. Permanent rehabilitation using a Full Encirclement Type B sleeve designed in accordance with ASME PCC-2 restored full design pressure capability through an independent load transfer mechanism. Thermoplastic I-Rod support redesign eliminated crevice geometry and addressed the root cause of corrosion initiation.

The key contributions of this study are:

- Formalisation of deterministic cross-standard integration into a structured integrity governance architecture.
- Demonstration that MAWPr-based pressure capacity verification must supersede corrosion rate extrapolation when severe local metal loss exists.
- Clarification of the distinction between geometric acceptability (RSF) and pressure containment adequacy (MAWPr).
- Integration of rehabilitation engineering and recurrence elimination into a unified decision pathway.

The SCIDM framework advances CUPS management beyond reactive repair toward structured structural governance and establishes a robust baseline for future reliability-based and probabilistic research development. ■

REFERENCES

[1] American Petroleum Institute. (2016). API 570: *Piping inspection code: In-service inspection, rating, repair, and alteration of piping systems* (4th ed.).

[2] American Petroleum Institute. (2020). API 571: *Damage mechanisms affecting fixed equipment in the refining industry* (3rd ed.).

[3] American Petroleum Institute. (2016). API 574: *Inspection practices for piping system components* (4th ed.).

[4] American Petroleum Institute, & American Society of Mechanical Engineers. (2016). *API 579-1/ASME FFS-1: Fitness-for-service* (3rd ed.).

[5] American Society of Mechanical Engineers. (n.d.). ASME B31.3: *Process piping*. ASME Code for Pressure Piping.

[6] American Society of Mechanical Engineers. (n.d.). *ASME PCC-2: Repair of pressure equipment and piping* (Article 206: Full encirclement sleeves).

[7] Sumitomo Chemical Co., Ltd. (n.d.). *Fitness-for-service (FFS) technology development and application.*

[8] API 579 User Guide Committee. (n.d.). *Fitness-for-service: API 579 user guide.* American Petroleum Institute.

[9] Costa, E. M., Dedavid, B. A., Santos, C. A., Lopes, N. F., Fraccaro, C., Pagartanidis, T., & Lovatto, L. P. (2022). Crevice corrosion on stainless steels in oil and gas industry: A review of techniques for evaluation, critical environmental factors and dissolved oxygen. *Engineering Failure Analysis, 143,* 106955.

[10] Li, Y., Mu, J., Cui, Z., & Wang, X. (2022). The crevice corrosion behavior of N80 carbon steel in acidic NaCl solution: The effect of O_2. *Materials and Corrosion, 73*(2), 281–290.

[11] Kelly, R. G., Scully, J. R., Shoesmith, D. W., & Buchheit, R. G. (2016). *Electrochemical techniques in corrosion science and engineering.* CRC Press.

[12] Roberge, P. R. (2000). *Handbook of corrosion engineering.* McGraw-Hill.

[13] Melchers, R. E. (2014). Probabilistic modelling of marine corrosion for structural reliability assessment. *Structural Safety, 50,* 1-8.

[14] Melchers, R. E. (2021). New insights from probabilistic modelling of corrosion in structural reliability analysis. *Structural Safety, 88,* 102034.

[15] Wang, T., Feng, K., Ling, J., Liao, M., Yang, C., Neubeck, R., & Liu, Z. (2024). Pipeline condition monitoring towards digital twin system: A case study. *Journal of Manufacturing Systems, 73,* 256–274.

[16] British Standards Institution. (n.d.). *BS EN ISO 12944: Paints and varnishes: Corrosion protection of steel structures by protective paint systems.*

PROFILE

PRAGASH KRISHNASAMY is a Professional Chartered Mechanical Engineer with over 20 years of experience in project engineering, asset integrity and reliability engineering, engineering assurance, and regulatory assurance within the oil and gas and petrochemical industries. His expertise encompasses corrosion engineering, Fitness for Service assessment, Risk-Based Inspection, mechanical integrity, pressure equipment, piping systems and integrity management for offshore and onshore facilities. He holds a Master of Science in Asset Management and Maintenance and internationally recognised professional certifications in API inspection, CSWIP welding inspection, IIW welding engineering, and Offshore Self-Regulation Inspection (OSRi). His current research focuses on asset integrity and reliability engineering, engineering decision frameworks, corrosion management, structural integrity assessment, digital asset management, and artificial intelligence applications for predictive asset integrity and reliability, including the development of the Structured CUPS Integrity Decision Model (SCIDM).
Email address: pragash.krishnasamy@gmail.com