



# 設計一套高效且具成本效益的腐蝕劣化機制診斷與檢測規劃系統

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在工業製程中，管線與容器被廣泛用於運輸及儲存不同流體，且操作條件各異。隨著時間推移，這些設備會因腐蝕而逐漸劣化，嚴重影響設備完整性、運作安全及維護成本。若無法及時有效地防止或偵測腐蝕，可能導致嚴重意外事故，如洩漏、火災或爆炸，危及人員安全、環境保護與經濟損失。

傳統上，腐蝕診斷與預防高度依賴經驗豐富的專家，他們透過分析材料種類、流體組成、操作條件及歷史故障資料，判斷可能的腐蝕機制並提出適當的預防措施。然而，派遣這些專家成本高昂且人力有限，且人為判斷易受主觀因素影響，可能導致決策不一致或延遲。

此外，業主近年明確要求 EPC 承包商進行腐蝕劣化機制評估，例如中鼎公司參與的 LR2、P1、LIWA 以及 RAPID 等專案。此類評估協助業主量化設備性能、了解故障風險並推動主動管理策略。對 EPC 承包商而言，提供快速且精準的腐蝕診斷及檢查計畫，已

不僅是法規要求，更是油氣、石化與電力產業的競爭優勢。

因此，迫切需要一套更智能、系統化的腐蝕管理方案，降低對專家依賴，同時提升腐蝕診斷與檢測規劃的準確性、效率與一致性。本文探討基於結構化資料庫與專家系統技術的系統設計。

## 系統架構與資料庫建置

腐蝕現象多樣且複雜，受化學成分、溫度、壓力、機械應力及環境條件等多重因素影響。常見腐蝕機制包含胺類腐蝕、應力腐蝕開裂、碳酸腐蝕、高溫氧化、熱疲勞、潛變及保溫層下腐蝕（CUI）等如圖 1 所示。解決此複雜問題須結合專家知識、穩健資料管理及分析能力。

高效系統架構包含感測器資料、資料整合、腐蝕診斷、檢測規劃與使用者介面，整

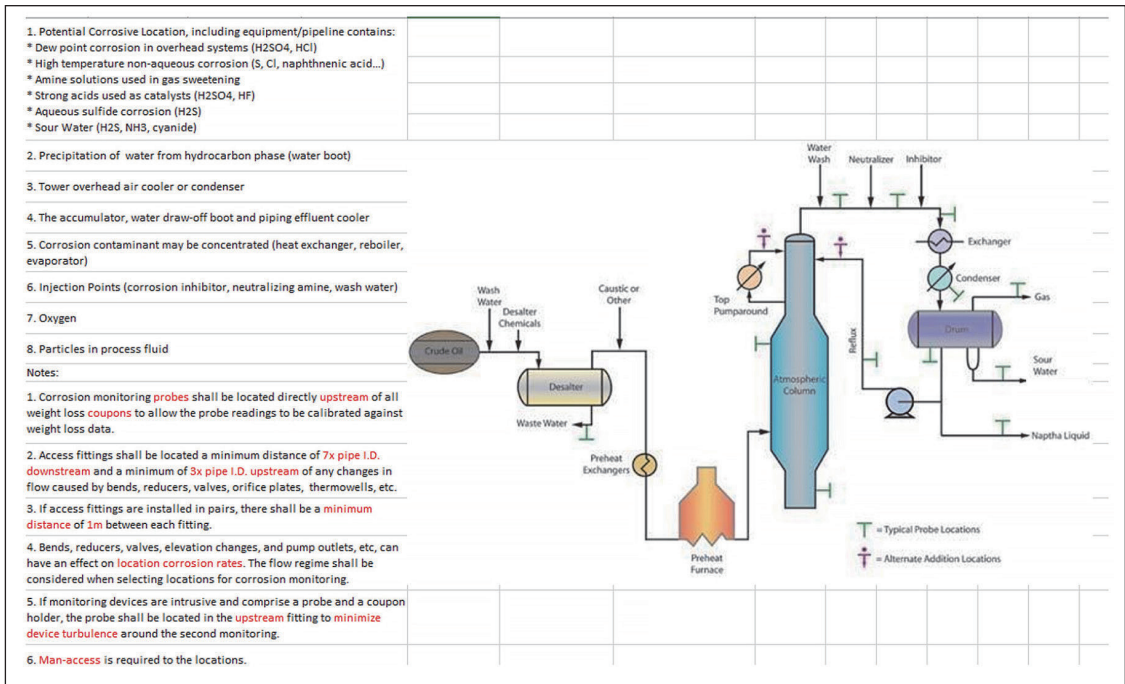


圖 1 工業管線及容器示意，標示常見腐蝕位置及損壞。

個系統運作的基礎功能階層與流程架構則繪製於圖 2。

- 感測器資料：收集壓力、溫度及腐蝕速率等現場感測數據。
- 資料整合：匯聚文獻、案例及國際標準（如 API 571）中的腐蝕知識。
- 腐蝕機制診斷：利用設備材料、操作溫度、壓力與流體化學等輸入參數，自動判斷可能腐蝕機制。
- 檢測與監控規劃：依據工廠類型與作業環境，提供腐蝕監測裝置配置及檢查時程建議。
- 使用者友善介面：設計多用戶可用的資料庫與直覺操作界面，促進不同工廠廣泛採用。

此系統架構促成腐蝕診斷與檢測規劃的自動化，提升決策可靠性，降低維護成本，增進工廠安全與運作完整性。

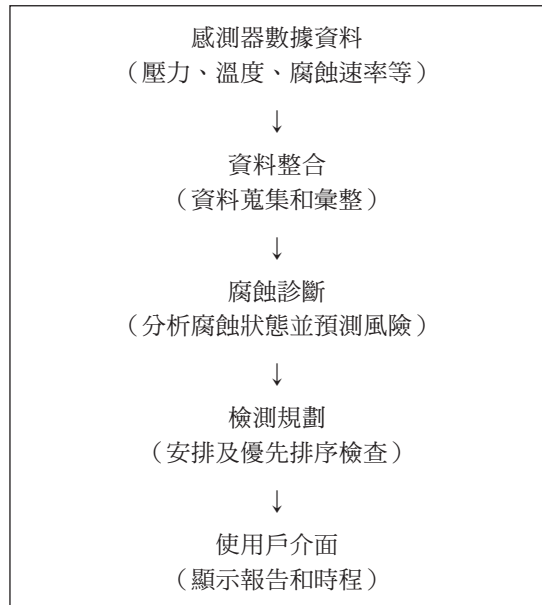


圖 2 系統架構圖，展示感測器資料、資料整合、腐蝕診斷、檢測規劃及使用者介面。



Common Damage Mechanisms									
Type	Mechanism	Material/Composition	Root Cause			Equipment/Location	Safeguard	Inspection	Remark
			Operating Temperature	Chemical Factor/Content	Physical Condition/Environment Factor				
Stress Corrosion Cracking	Amine Cracking	Carbon Steel and Low Alloy Steel	—	Amines (MEA, DEA, DIPA, MDEA)	—	—	1. PWHT 2. Use solid or clad SS, alloy 400	1. Ultrasonic Test 2. Penetration Test 3. Eddy Current Test/Remote Field Eddy Current Test for heat exchanger 4. Magnetic Test	
	Creep	300 Series Stainless Steel	> 480°C	—	1. Long periods of plastic deformation lower than yield strength	Furnace tubes and supports	Avoid stress concentration	1. Ultrasonic Test 2. Radiographic Test	
	Fatigue	Thermal Fatigue	—	$\Delta T > 99^\circ\text{C}$	—	—	Welding area, Stress concentrated area, Heat exchanger, Steam system, Coke, Catalyst Regeneration	1. Reduce temperature cycling 2. Reduce stress concentration 3. Install Liner or Sleeve	
Mechanical Fatigue		Carbon Steel, Low Alloy Steel, or Stainless Steel	—	—	1. Repeated Stress 2. Vibration 3. Pressure Variation 4. Thermal Cycling	Welding area, Stress concentrated area, Rotating Equipment, Reciprocating parts in pumps and compressors, Cyclic equipment	1. Loading mitigation 2. Minimize stress concentration 3. Stabilizer installation	1. Visual Examination 2. Penetration Test 3. Magnetic Test 4. External Shear Wave Ultrasonic Test	
Corrosion Fatigue		—	—	Corrosive Substance	1. Cyclic stress loading 2. Vibration	Welding area, Stress concentrated area, Rotating Equipment, Steam drum heads	1. Minimize the differential strains 2. Minimize residual welding		Pitting promotes corrosion fatigue
Mechanical & Metallurgical Failure									

圖 3 示意圖說明常見腐蝕機制，如胺類腐蝕、應力腐蝕開裂、機械與冶金失效及熱疲勞。

## 資料蒐集與分析

自動化的第一步是從多種廠別蒐集全面資料，並針對不同工業環境中常見的失效態樣（如圖 3 所示）進行分類。包括：

- 芳香烴廠（AROMA）
- 重油觸媒裂解廠（RFCC）
- 環氧乙烷／乙二醇廠（EO/EG）
- 酚類生產廠
- 蒸汽裂解廠
- 燃燒氣脫硫廠（FGRS）
- 電廠

對每種廠別，詳細分析腐蝕機制及劣化環路，其對應關係整合如圖 4。此外，深入研究 14 類腐蝕與損壞機制，包括：

- 胺腐蝕與胺應力腐蝕開裂
- 鹼性應力腐蝕開裂
- 碳酸腐蝕
- 高溫硫化與氧化腐蝕
- 多硫酸鹽應力腐蝕開裂
- 硫化物應力腐蝕開裂
- 酸性水腐蝕
- 濕硫化氫應力腐蝕開裂
- 熱疲勞



- 潛變
- 保溫層下腐蝕及侵蝕

並收集腐蝕監測方法、感測器配置及事故調查報告（包括腐蝕引發之洩漏、火災、爆炸）以豐富知識庫。

### 資料庫建置

第二步設計關聯式資料庫，整理腐蝕診斷相關關鍵參數，資料庫內部的實體關係與

邏輯架構如圖 5 所示，其涵蓋的欄位包含：

- 製程流體組成（如 H<sub>2</sub>S、H<sub>2</sub>、NH<sub>3</sub>、硫化物）
- 設備及管線材料（碳鋼、不銹鋼、合金鋼）
- 運行條件（溫度、壓力、流速）
- 化學性質（pH 值、腐蝕物質濃度）
- 物理及環境條件（濕度、保溫狀況）
- 設備位置與風險因子
- 推薦預防措施與腐蝕類型
- 偵測方法與檢查規劃

Unit	Equipment/Section	Corrosion		CMS			Remark
		Mechanism	Corrosives	Type	Purpose	Installation Location	
Crude Distillation	Main Tower Top	Acid Corrosion	Condensed HCl	Coupon, ER Probe	Corrosion inhibitor, amine, and wash water efficacy monitoring	1. Down Stream of Condenser 2. Down stream of reflux drum boot 3. Down stream of injection point (wash water, amine, inhibitor...)	
	Main Tower Bottom	High Temperature Acid Corrosion	Naphthenic Acid	Coupon, ER Probe	Feed monitoring	Down stream of bottom exit	200-400°C
	De-butanizer Top	Acid Corrosion	H <sub>2</sub> S	Coupon, ER Probe, Hydrogen Probe	Corrosion inhibitor, amine, and water cleaning efficacy monitoring	1. Down Stream of Condenser 2. Down stream of reflux drum boot 3. Down stream of injection point (wash water, amine, inhibitor...)	
RFCC/FCC	Main Tower Top	Wet H <sub>2</sub> S Damage	H <sub>2</sub> S, cyanide	Coupon, ER Probe, Hydrogen Probe	Corrosion inhibitor, amine, and wash water efficacy monitoring	1. Down Stream of Condenser 2. Down stream of reflux drum boot 3. Down stream of injection point (wash water, amine, inhibitor...)	
	Stabilizer Tower Top	Acid Corrosion	H <sub>2</sub> S				
Sour Water Stripping	Sour Water Stripper Top	Wet H <sub>2</sub> S Damage	H <sub>2</sub> S, cyanide, NH <sub>3</sub>	Coupon, ER Probe, Hydrogen Probe	Corrosion inhibitor, amine, and wash water efficacy monitoring	1. Down Stream of Condenser 2. Down stream of reflux drum boot 3. Down stream of injection point (wash water, amine, inhibitor...)	
	Sour Water Feed						
	Sour Water Stripper Bottom						

圖 4 不同廠別及其相關腐蝕劣化情形圖表



Mechanism		Material/Composition	Root Cause			Equipment/Location	Safeguard	Inspection	Remark	
			Operating Temperature	Chemical Factor/Content	Physical Condition/Environment Factor					
Uniform/Localized Thinning	Sulfuric Acid Dew Point Corrosion	Carbon Steel or Stainless Steel	Below Dew Point $(H_2SO_4: < 138^\circ C, HCl < 54^\circ C)$	$SO_2, SO_3, HCl$ produced by combustion of S and Cl (pH < 2)	—	Flue Duct, Heat Exchanger Downstream	1. Maintain T over dew point 2. Avoid using 300 series SS if Cl presents	1. Visual Test 2. Ultrasonic Test 3. Eddy Current Test (for heat exchanger, CS only) 4. Real-Time Profile X-Ray for small tubes		
	Flue Gas Dew Point Corrosion					Flue Duct				
	Amine Corrosion		> 104°C	MEA, DIPA (acid gas), $H_2O$		De-acid gas equipments, Crude unit, Coker, FCC, hydrogen reforming, hydroprocessing, and tail-gas units				1. Decrease fluid velocity 2. Use anti-corrosive SS 3. Add inhibitors
	Casutic Corrosion		> 66°C for CS and 300 series SS (critical T: > 92°C)	NaOH, KOH		Boiler, Heat exchanger, Crude Unit, Furnace tubes, Desulfurization Unit				1. Proper design 2. Use 400 series SS or Ni-based alloys
	Carbon Acid Corrosion		—	$CO_2$ in water (>20%)		DIPA Regenerator Top				1. Use 300 or 400 series SS 2. Add amine as inhibitor (pH > 6)
	Cooling Water Corrosion		—	Steam & Cooling Water		Steam System				1. Proper design, operation, and chemical treatment 2. T < 60°C 3. Maintain min. water velocity

圖 5 腐蝕資料庫關聯模型示意圖

## 檢索與查詢系統設計

為提升使用便捷性，系統支援多參數搜尋，其直覺的「多參數腐蝕查詢介面」如圖 6 所示，允許用戶查詢：

- 各廠別及關鍵設備之潛在腐蝕機制
- 推薦的腐蝕監測裝置與檢查計劃
- 根據流體與運行條件適合的設備與管線材料
- 優化運轉安全的操作窗口與腐蝕裕度
- 針對特定腐蝕機制的詳細檢查計畫

## 使用者介面與軟體開發

採用現有資料庫軟體工具設計友善介面，方便廠方人員輸入及檢索資訊。軟體整

合基於規則的專家系統，透過程式邏輯決策（演算法核心流程參見圖 7），實現：

- 根據輸入資料自動辨識可能腐蝕機制
- 建議適當預防與偵測方法
- 自動生成檢查時程與監控計劃

此方法降低對專家依賴，確保診斷結果一致且可重複。

## 成果與效益

系統大量借鑑 API 571 及其他腐蝕標準，將腐蝕機制由描述文字轉化為結構化資料表（基準參數表範例參見圖 8），包含：



Unit	Equipment/Section	Corrosion		CMS			Remark
		Mechanism	Corrosives	Type	Purpose	Installation Location	
Crude Distillation	Main Tower Top	Acid Corrosion	Condensed HCl	Coupon, ER Probe	Corrosion inhibitor, amine, and wash water efficacy monitoring	1. Down Stream of Condenser 2. Down stream of reflux drum boot 3. Down stream of injection point (wash water, amine, inhibitor...)	
	Main Tower Bottom	High Temperature Acid Corrosion	Naphthenic Acid	Coupon, ER Probe	Feed monitoring	Down stream of bottom exit	200-400°C
	De-butanizer Top	Acid Corrosion	H <sub>2</sub> S	Coupon, ER Probe, Hydrogen Probe	Corrosion inhibitor, amine, and water cleaning efficacy monitoring	1. Down Stream of Condenser 2. Down stream of reflux drum boot 3. Down stream of injection point (wash water, amine, inhibitor...)	

圖 6 多參數腐蝕查詢介面示意圖

	A	B	C	D	E	F	G	H
1	Damage Mechanism Configurations		Macro Version: 0.3.0.0					
2	Values Worksheet		Input Arguments Column Index Mappings				Comparer Types	
4	Worksheet name	Input	Input sheet columns	Rule sheet columns	Comparer			AnyItems
5	Starting row index	4	8	6	NumericRange			Identical
6	Validate on change	TRUE	10	3	Identical			NumericRange
7			12	5	AnyItems			RuleContainsValue
8	Rules Worksheet							
9	Worksheet name	Damage Mechanism						
10	Starting row index	4						
11			Output Column Index Mappings					
12			Input sheet columns	Rule sheet columns	As Heading	Format Macro		
14			13	10	TRUE	FormatDamageMechanism		
15			14	11	FALSE	MyCustomFormat		
16			15	12	FALSE	MyCustomFormat		
17								
18								
19								
20								

圖 7 專家系統邏輯流程圖，顯示輸入、規則判斷與輸出建議。

- 設備材料類型( 碳鋼、不銹鋼、低合金鋼)
- 運行溫度與壓力範圍
- 流體化學成分( 如硫化氫、胺類、酸)

此外，診斷規則基於文獻及專家知識編寫，用戶輸入材料、溫度、壓力與流體組成後，能輕鬆判定最可能的腐蝕機制及建議監測和檢查策略。例如：

當輸入參數匹配或相近，系統視為相同腐蝕現象，透過規則邏輯判斷腐蝕風險。

- 若材料為碳鋼，溫度 50°C，流體含 H<sub>2</sub>S，



**5.1.2.3 Wet H<sub>2</sub>S Damage (Blistering/HIC/SOHIC/SSC)**

**5.1.2.3.1 Description of Damage**  
This section describes four types of damage that result in blistering and/or cracking of carbon steel and low alloy steels in wet H<sub>2</sub>S environments.

a) **Hydrogen Blistering**  
Hydrogen blisters may form as surface bulges on the ID, the OD or within the wall thickness of a pipe or pressure vessel. The blister results from hydrogen atoms that form during the sulfide corrosion process on the surface of the steel, that diffuse into the steel, and collect at a discontinuity in the steel such as an inclusion or lamination. The hydrogen atoms combine to form hydrogen molecules that are too large to diffuse out and the pressure builds to the point where local deformation occurs, forming a blister. Blistering results from hydrogen generated by corrosion, not hydrogen gas from the process stream. (Figure 5-34 and Figure 5-35.)

b) **Hydrogen Induced Cracking (HIC)**  
Hydrogen blisters can form at many different depths from the surface of the steel, in the middle of the plate or near a weld. In some cases, neighboring or adjacent blisters that are at slightly different depths (planes) may develop cracks that link them together. Interconnecting cracks between the blisters often have a stair step appearance, and so HIC is sometimes referred to as "stepwise cracking" (Figure 5-36, Figure 5-37 and Figure 5-38.)

c) **Stress Oriented Hydrogen Induced Cracking (SOHIC)**  
SOHIC is similar to HIC but is a potentially more damaging form of cracking which appears as arrays of cracks stacked on top of each other. The result is a through-thickness crack that is perpendicular to the surface and is driven by high levels of stress (residual or applied). They usually appear in the base metal adjacent to the weld heat affected zones where they initiate from HIC damage or other cracks or defects including sulfide stress cracks (Figure 5-39 and Figure 5-40.)

d) **Sulfide Stress Cracking (SSC)**  
Sulfide Stress Cracking (SSC) is defined as cracking of metal under the combined action of tensile stress and corrosion in the presence of water and H<sub>2</sub>S. SSC is a form of hydrogen stress cracking resulting from absorption of atomic hydrogen that is produced by the sulfide corrosion process on the metal surface.  
SSC can initiate on the surface of steels in highly localized zones of high hardness in the weld metal and heat affected zones. Zones of high hardness can sometimes be found in weld cover passes and attachment welds which are not tempered (softened) by subsequent passes. PWHT is beneficial in reducing the hardness and residual stresses that render steel susceptible to SSC. High strength steels are also susceptible to SSC but these are only used in limited applications in the refining industry. (Figure 5-42 and Figure 5-43). Some carbon steels contain residual elements that form hard areas in the heat affected zones that will not temper at normal stress relieving temperatures. Using preheat helps minimize these hardness problems.

**5.1.2.3.2 Affected Materials**  
Carbon steel and low alloy steels.

**5.1.2.3.3 Critical Factors**  
a) The most important variables that affect and differentiate the various forms of wet H<sub>2</sub>S damage are environmental conditions (pH, H<sub>2</sub>S level, contaminants, temperature), material properties (hardness, microstructure, strength) and tensile stress level (applied or residual). These factors are outlined below.

Operating Condition (Input)		Material of Equipment/Piping (Selection Menu)	Temperature (°C) (Blank Filling)	Environmental Condition	Damage Mechanism (Output)
Composition (Selection Menu)	Composition Detail				
1 NaOH & KOH	> 50ppm NaOH, KOH	Carbon Steel	60-115	NA	Caustic Cracking
2 NaOH & KOH	> 50ppm NaOH, KOH	Low Alloy Steel	NA	NA	Caustic Cracking
3 NaOH & KOH	> 50ppm NaOH, KOH	300 Series SS	> 125	NA	Caustic Cracking
4 Amine	Amine (MEA, DEA)	Carbon Steel	NA	NA	Amine Cracking
5 Amine	Amine (MEA, DEA)	Low Alloy Steel	NA	NA	Amine Cracking
6 H <sub>2</sub> S	H <sub>2</sub> S gas	Carbon Steel	20-150	NA	Wet H <sub>2</sub> S Damage (Hydrogen Cyanide Cracking)
7 H <sub>2</sub> S	H <sub>2</sub> S gas	Low Alloy Steel	20-150	NA	Wet H <sub>2</sub> S Damage (Hydrogen Cyanide Cracking)
8 H <sub>2</sub> S	> 50ppm H <sub>2</sub> S in water	Carbon Steel	20-150	NA	Wet H <sub>2</sub> S Damage (Hydrogen Cyanide Cracking)
9 H <sub>2</sub> S	> 50ppm H <sub>2</sub> S in water	Low Alloy Steel	20-150	NA	Wet H <sub>2</sub> S Damage (Hydrogen Cyanide Cracking)
10 H <sub>2</sub> S	Some H <sub>2</sub> S in water	Carbon Steel	20-150	NA	Wet H <sub>2</sub> S Damage (Hydrogen Cyanide Cracking)
11 H <sub>2</sub> S	Some H <sub>2</sub> S in water	Low Alloy Steel	20-150	NA	Wet H <sub>2</sub> S Damage (Hydrogen Cyanide Cracking)
12 H <sub>2</sub> S	20ppm HCN & some H <sub>2</sub> S in water	Carbon Steel	20-150	NA	Wet H <sub>2</sub> S Damage (Hydrogen Cyanide Cracking)
13 H <sub>2</sub> S	20ppm HCN & some H <sub>2</sub> S in water	Low Alloy Steel	20-150	NA	Wet H <sub>2</sub> S Damage (Hydrogen Cyanide Cracking)
14 H <sub>2</sub> S	H <sub>2</sub> S gas	Carbon Steel	20-150	NA	Wet H <sub>2</sub> S Damage

圖 8 摘自 API 571 標準的腐蝕機制參數表範例

則可能預測碳鋼硫化物應力腐蝕破裂。

- 若不銹鋼在含胺酸性條件下操作，則可能為胺應力腐蝕破裂。

- 確認的腐蝕劣化機制
- 推薦的腐蝕監測系統與裝置位置
- 建議的檢查時程與操作窗口
- 腐蝕裕度評估

系統最後可自動生成完整報告（產出範本如圖 9 所示），內容涵蓋：

報告幫助操作人員及維護團隊有效優先安排檢查與預防措施。

Location	Equipment	Tag Number	API 571 Known Damage Mechanism	Operating Condition (Input) Temperature (°C)	Material of Equipment/Piping Composition	Damage Mechanism (Output) Possible Damage Mechanisms	Counter Measures (Output) Prevention or Mitigation Approaches against Possible Damage Mechanisms	Inspection Plan (Output) Testing Approaches against P Damage Mechanisms
Main Fractionator top	Main Fractionator	1311-C-001	Wet H <sub>2</sub> S Damage	50	H <sub>2</sub> S			
Main Fractionator Bottom	Main Fractionator	1311-C-001	?					
Downstreams of Main Tower top heat exchanger (Condenser)			Flue Gas Dew Point Corrosion					
Main Tower bottom			High Temperature Naphthenic Corrosion					
Rich Amine System	Rich Amine Drum	D-1101	Wet H <sub>2</sub> S Damage					
Lean Amine System	Lean Amine Pump	P-1102A/B	Amine Corrosion					
Sour Gas Loop	Sour Gas Drum	D-1301	Wet H <sub>2</sub> S Damage					
Sour Water Loop	Sour Water Drum	D-1201	Wet H <sub>2</sub> S Damage					
Steam Reboiler System	Steam Condensate Drum	D-1203A/B	Corrosion Under Insulation					
Main Reactor	Main Reactor	R-1301	High Temperature Sulfidation					
Flue Gas Reactor OVHD	Flue Gas Reactor	R-1302	Sulfuric Acid Dew Point Corrosion					
			Flue Gas Dew Point Corrosion					

圖 9 系統產生的腐蝕診斷與檢測規劃報告範例



## 腐蝕診斷與檢測規劃系統實用優勢

- 提升操作視窗完整性 (IOW)：操作人員可根據可靠的腐蝕風險評估維持更安全的操作條件。
- 目標明確的檢查與維護：檢查人員聚焦高風險區域，優化資源分配。
- 強化事故調查：詳盡的腐蝕機制記錄與診斷邏輯有助事故根因分析。
- 降低專家依賴：自動化複雜診斷流程，減少稀缺專家不足及主觀錯誤。
- 節省成本：有效管理腐蝕，減少意外故障、停工及維修費用。

## 關鍵結論

本文簡述了一套高效且具成本效益的腐蝕劣化機制診斷及檢測規劃系統。該系統能自動辨識腐蝕機制並提供可行的檢測與監控計劃，促進主動腐蝕管理。未來可持續擴充資料庫涵蓋更多廠別與腐蝕機制、提升使用者介面體驗、整合即時監控數據進行動態風險評估，以及透過現場數據驗證與精進診斷演算法。

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