

**API 571 RP: Damage Mechanisms Affecting Fixed
Equipment in the Refining Industry
2nd Edition, APRIL 2011**

(Rev 01)(09.Apr.2017)

Sr #	Sec.	Damage Mechanism	Definition	Defect	Temperature °F (°C)	Affected Materials	Resistant Materials	Critical Factors	Affected Units /Equipment	Morphology	Mitigation	Inspection	Related Mechanism	Comments	
	4	General Damage Mechanism - All Industries													
	4.2	Mechanical and Metallurgical Failure Mechanisms													
1	4.2.1	Graphitization	Carbide phases may decompose into graphite nodules	Loss in strength, ductility, and/or creep resistance	800-1100 °F (427 - 593 °C)	Some grades of carbon steel and 0.5Mo steels	Addition of 0.7% Chromium	Chemistry, Stress, Temp., and Time of exposure	Hot-wall piping and equipment in the FCC, catalytic reforming and coker units	Not visible or readily apparent	Use Chromium containing Alloys in operation above 800 °F	Metallography	Spheroidization	Change in microstructures. Spheroidization tends to occur preferentially above 1025°F (551°C) , while graphitization predominates below this temperature	
2	4.2.2	Softening (Spheroidization)	Carbide phases may agglomerate from normal plate-like form to a spheroidal form	Loss in strength and/or creep resistance	850-1400 °F (440 - 760 °C)	CS and Low Alloy Steel	Annealed steels, Coarse grained structure	Metal chemistry, microstructure, exposure time, and temperature	Hot-wall piping and equipment in the FCC, catalytic reforming and coker units	Not visible or readily apparent	Minimizing long-term exposure to elevated temperatures	Metallography	Graphitization		
3	4.2.3	Temper Embrittlement	Metallurgical changes under long time exposure in the temp. range	Loss of toughness	650-1070 °F (343 - 577 °C)	2.25Cr-1Mo low alloy steel, 3Cr-1Mo, and high-strength low alloy, Cr-Mo-V rotor steels	C-0.5Mo, 1Cr-0.5Mo and 1.25Cr-0.5Mo alloy steels	Alloy steel composition, thermal history, metal temperature and exposure time	Hydroprocessing units, catalytic reforming units, FCC reactors, coker and visbreaking units	Not visible or readily apparent, catastrophic brittle fracture	Existing Material: Use Pressureizing sequence New Material: Limit levels of Mn, Si, P, Sn, Sb, As in base BM & consumables	Installation of Test blocks for periodic toughness measurement, and process conditions monitoring	N/A	Upward shift in the ductile-to-brittle transition temperature	
4	4.2.4	Strain Aging	Under the combined effects of deformation and aging at an intermediate temp.	Increase in hardness and strength with a reduction in ductility and toughness	Intermediate Temperature	Older vintage carbon steels and C-0.5 Mo low alloy steel	Steels made by BOF and fully killed with aluminum	Steel composition and manufacturing process determine steel susceptibility	Thick wall vessels manufactured from susceptible materials that have not been stress relieved	Damage not to be identified as strain aging until fracture	PWHT to weld repairs or Buttering, careful pressurizing below brittle fracture temp.	Inspection and monitoring are not used to control strain aging	Dynamic strain aging, Blue brittleness	BOF: Basic Oxygen Furnace	
5	4.2.5	885°F (475 °C) Embrittlement	Metallurgical change that can occur in alloys having ferrite phase, as a result of exposure in the temp. range	Loss in toughness	600-1000 °F (316 - 540 °C)	400 Series SS (e.g., 405, 409, 410, 410S, 430 and 446), Duplex stainless steels such as Alloys 2205, 2304 and 2507	Low ferrite or non-ferritic alloys,	Alloy composition, particularly chromium content, amount of ferrite phase, and operating temperature	any unit where susceptible alloys exposed to the embrittling temperature range	Not readily apparent with metallography, but can be identified by an increase in hardness	Use low ferrite or non-ferritic alloys, Reversed by de-embrittling heat treatment at 1100 °F or higher	Impact or bend testing	N/A	Damage is cumulative and results from the precipitation of an embrittling intermetallic phase that occurs most readily at appr. 885°F	
6	4.2.6	Sigma Phase Embrittlement	Formation of a metallurgical phase known as sigma phase as a result of high temp. exposure	Loss of fracture toughness	1000-1700 °F (538-927 °C)	Ferritic and martensitic SS, 300 SS (HK,HP), 400 SS (430,440), Duplex SS	SS (<17% Cr), Low Ferrite contents	Alloy composition, time and temperature	FCC Regenerator service, SS weld overlays and tube-to-tubesheet attachment welds SS heater tubes	Not visible or readily apparent. Particularly at welds or in areas of high restraint	Use alloys that are resistant to sigma formation or to avoid exposing the material to the embrittling range	Metallographic examination and impact testing	N/A	Precipitation of a hard, brittle intermetallic compound that can also render the material more susceptible to intergranular corrosion	
7	4.2.7	Brittle Fracture	Sudden rapid fracture under stress (residual or applied)	Material exhibits little or no evidence of ductility or plastic deformation	Below ductile-to-brittle transition temperature	Carbon steels and low Alloy, SS 400 series	Material with controlled chemical composition, special heat treatment and impact test verified	Fracture toughness, amount of stresses, flaw size, ductile-to-brittle transition temperature	Thick wall equipment, alkylation units, olefin units and polymer plants	Straight and non-branching cracks. Fracture surface will be composed largely of cleavage, with limited intergranular cracking	Controlling the operating conditions (pressure, temp.), Perform PWHT	Check for pre-existing flaws/defects.	Temper Embrittlement, Strain Aging embrittlement, 885°F Embrittlement, Sigma embrittlement	Brittle fracture is an "event" driven damage mechanism Main concern is for brittle fracture during startup, shutdown, or hydrotest /tightness testing	
8	4.2.8	Creep and Stress Rupture	Time dependent deformation of stressed components	Deformation leads to damage that may eventually lead to a rupture	High temperatures	All metals and alloys	N/A	Material, load, and temperature	Heater tubes in fired heaters, hot-wall catalytic reforming reactors and furnace tubes	Bulging before final fracture	Avoiding stress concentrators, minimize temperatures	A combination of techniques (UT, RT, EC, dimensional measurements and replication)	Reheat cracking	Increase of about 25°F (12°C) or an increase of 15% on stress can cut the remaining life in half or more, depending on the alloy	
9	4.2.9	Thermal Fatigue	Cyclic stresses caused by variations in temperature	Relative movement or differential expansion is constrained, particularly under repeated thermal cycling	Temperature swings exceeds about 200°F (93°C)	All materials of construction	N/A	Magnitude of the temperature swing and the frequency (number of cycles)	Mix points of hot and cold streams, coke drum skirts,	Surface cracks "Dagger-shaped", transgranular, and oxide filled	Best prevented through design and operation to minimize thermal stresses and thermal cycling	Visual examination, MT and PT, SWUT	Corrosion fatigue, Dissimilar metal weld cracking	Thermal fatigue cracks propagate transverse to the stress, Differential expansion of bimetallic welds	
10	4.2.10	Short Term Overheating – Stress Rupture	Permanent deformation occurring at relatively low stress levels as a result of localized overheating	Bulging and eventually failure by stress rupture.	N/A	All fired heater tube materials and common materials of construction	N/A	Temperature, time and stress	All boiler and fired heater tubes, Furnaces	Localized deformation or bulging on the order of 3% to 10% or more. Ruptures are characterized by open "fishmouth"	Minimize localized temp. excursions, minimize hot spots and localized overheating	Visual observation, IR monitoring	Creep/stress rupture	Time to failure will increase as internal pressures or loading decrease	
11	4.2.11	Steam Blanketing	When the heat flow balance is disturbed, individual bubbles join to form a steam blanket, a condition known as Departure From Nucleate Boiling (DNB)	Rupture can occur rapidly, as a result of short term overheating	N/A	Carbon steel and low alloy steels	N/A	Heat flux and fluid flow	All steam-generating units i.e. fired boilers, waste heat exchangers, superheaters and reheaters	Open burst with the fracture edges drawn to a near knife-edge, severe elongation of the grain structure due to the plastic deformation	Minimize flame impingement, Proper BFW treatment, Tubes should be visually inspected for bulging	Burners should be properly maintained to prevent flame impingement	Caustic corrosion (caustic gouging), Short term overheating	The flow of heat energy through the wall of the tube results in the formation of discrete steam bubbles (nucleate boiling) on the ID surface. The moving fluid sweeps the bubbles away	

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12	4.2.12	Dissimilar Metal Weld (DMW) Cracking	Cracking of dissimilar metal welds occurs in the ferritic side of a weld between an austenitic and a ferritic material operating at high temp.	Cracking can result from creep damage, from fatigue cracking, from sulfide stress cracking or hydrogen disbonding	High temperatures	Carbon Steel and low alloy steel, material combinations that have widely differing thermal expansion coefficients	N/A	Type of filler metal, heating and cooling rate, metal temp., time at temp., weld geometry and thermal cycling	Clad piping, Hydroprocessing exchanger inlet and outlet piping etc.	Cracks form at the toe of the weld in the heat-affected zone of the ferritic material	Joints of Nickel base filler metals and CS	100% PT after buttering, 100% UT on butter layer after PWHT, 100% RT, 100% UT, PMI	Thermal fatigue, corrosion fatigue, creep, and sulfide stress cracking	Cracking can occur due to different coefficients of thermal expansion between ferritic and austenitic which differ by about 25 to 30% or more.
13	4.2.13	Thermal Shock	High and non-uniform thermal stresses develop over a relatively short time in a piece of equipment due to differential expansion or contraction	A form of thermal fatigue cracking	High temperatures	All metals and alloys	N/A	Magnitude of temperature differential and the coefficient of thermal expansion of the material	FCC, cokers, catalytic reforming and high severity hydroprocessing units	Surface initiating cracks may also appear as "craze" cracks	Prevent interruptions in the flow of high temp. lines, install thermal sleeves to prevent liquid impingement, Review hot/cold injection points	Highly localized and difficult to locate, PT and MT can be used to confirm cracking	Thermal fatigue	Thermal shock usually occurs when a colder liquid contacts a warmer metal surface
14	4.2.14	Erosion/Erosion – Corrosion	Erosion is the mechanical removal of surface material as a result of relative movement between, or impact from solids, liquids, vapor. Erosion-corrosion is a the damage that occurs when corrosion contributes to erosion by removing protective films or scales, or by exposing the metal surface to further corrosion under the combined action of erosion and corrosion		N/A	All metals, alloys and refractories	N/A	Velocity and concentration of impacting medium, the size and hardness of impacting particles, the hardness and corrosion resistance of material, and the angle of impact	All types of equipment exposed to moving fluids	Localized loss in thickness in the form of pits, grooves, gullies, waves, rounded holes and valleys	Improvements in design involve changes in shape, geometry and materials selection	Visual examination , UT checks or RT for metal loss, IR scans are used to detect refractory loss	Cavitation, liquid impingement erosion, fretting	Susceptible locations: Bends, elbows, tees and reducers; downstream of letdown valves and block valves; pumps; blowers; propellers; impellers; agitators; agitated vessels; heat exchanger tubing; etc.
15	4.2.15	Cavitation	Formation and instantaneous collapse of innumerable tiny vapor bubbles	Cavitation is a form of erosion	N/A	Copper and brass, cast iron, carbon steel, low alloy steels, 300 Series SS, 400 Series SS and nickel base alloys	N/A	Inadequate NPSH, Temp. approaching to Boiling Point, presence of solid or abrasive particles	Pump casings, pump impellers (low pressure side) and in piping downstream of orifices or control valves	Sharp-edged pitting but may also have a gouged appearance in rotational components	Avoid conditions that allow the absolute pressure to fall below the vapor pressure of the liquid or by changing the material properties	Acoustic monitoring, VT, UT, RT	Liquid impingement or erosion	Damage occurs only in localized low-pressure zones
16	4.2.16	Mechanical Fatigue	Exposed to cyclical stresses for an extended period, often resulting in sudden, unexpected failure	Stresses can arise from either mechanical loading or thermal cycling and are typically well below the yield strength of the material	N/A	All engineering alloys	CS & T: These materials exhibit an endurance limit below which fatigue cracking will not occur, regardless of the number of cycles	Geometry, stress level, number of cycles, and material properties	Thermal Cycling: Coke drums, auxiliary boiler, water washing systems, Mechanical Loading: Pressure Swing Absorbers, steam reducing stations	"Clam shell" type fingerprint that has concentric rings called "Beach marks" emanating from the crack initiation site	Good design, generous radius along edges and corners, good fitup, remove defects like burs or lips, grinding marks etc	PT, MT and SWUT, VT of small diameter pipin, Vibration monitoring	Vibration induced fatigue	Ratio of endurance limit over UTS is typically between 0.4 and 0.5, Number of cycles 106 -107
17	4.2.17	Vibration-Induced Fatigue	Cracks are produced as the result of dynamic loading due to vibration, water hammer, or unstable fluid flow	Form of mechanical fatigue	N/A	All engineering materials	N/A	Amplitude, Frequency of vibration, and fatigue resistance	Socket welds and small bore piping at or near pumps, Small bore bypass lines, Small branch connections, Safety relief valves, failure of the refractory and/or the anchoring system	Crack initiating at a point of high stress or discontinuity such as a thread or weld joint	Design and the use of supports, Install gussets or stiffeners on Small Bore Piping (SBP)	Visible signs of vibration, pipe movement or water Audible sounds of vibration, PT, MT	Mechanical fatigue, Refractory degradation	A lack of or excessive support or stiffening allows vibration and possible cracking. Heat exchanger tubes may be susceptible to vortex shedding
18	4.2.18	Refractory Degradation	Thermal insulating and erosion resistant refractories are susceptible to various forms of mechanical damage (cracking, spalling and erosion) as well as corrosion due to oxidation, sulfidation and other high temperature mechanisms.		N/A	Insulating ceramic fibers, castables, refractory brick and plastic refractories	N/A	Refractory selection, design and installation	FCC reactor regenerator vessels, piping, cyclones, slide valves and internals; in fluid cokers; cold shell catalytic reforming reactors; waste heat boilers	Signs of excessive cracking, spalling or lift-off from the substrate, washed away or thinned	Proper selection of refractory, anchors and fillers and their proper design and installation	Visual inspection during shutdowns, IR to monitor for hot spots	Oxidation, Sulfidation, Flue gas dew point corrosion	Refractory type and density must be selected to resist abrasion and erosion
19	4.2.19	Reheat Cracking	Cracking of a metal due to stress relaxation during Post Weld Heat Treatment (PWHT) or in service at elevated temperatures		Above 750°F (399 °C)	Low alloy steels, 300 Series SS and nickel base alloys such as Alloy 800H	N/A	Composition of Material, grain size, residual stresses from fabrication, section thickness , notches and stress concentrators, metal strengths etc.	Heavy wall vessels in areas of high restraint including nozzle welds and heavy wall piping, HSLA steels are very susceptible to reheat cracking	Intergranular and can be surface breaking or embedded depending on the state of stress and geometry	Minimize restraint during welding and PWHT	UT & MT for CS, UT & PT for SS, Embedded cracks: UT	Stress relief cracking and stress relaxation cracking	More likely to occur in thicker sections and higher strength materials
20	4.2.20	Gaseous Oxygen-Enhanced Ignition and Combustion	The spontaneous ignition or combustion of metallic and nonmetallic components can result in fires and explosions in certain oxygen-enriched gaseous environments		N/A	CS, Titanium alloys, Plastics, rubbers, and hydrocarbon lubricants	SS, Copper alloys (with >5% Cu & >50% Ni)	Pressure, Oxygen content, line velocity, component thickness, temperature, design and piping configuration, cleanliness	Valves, regulators, and other impingement areas are potentially vulnerable. Non-metals such as those used for seats and seals, are easier to ignite than metals	External heat damage (glowing pipe or heat tint) is a strong indication of an internal fire	Keep systems clean, Maintain velocity within recommended limits, use only "oxygen compatible" lubricants	Tell-tale signs of a minor fire such as external heat damage, or signs of malfunctioning valves	N/A	Avoid velocities that are nominally above 100 feet/second (30 m/sec) in gaseous oxygen
4.3 Uniform or Localized Loss of Thickness														
21	4.3.1	Galvanic Corrosion	Occurs at the junction of dissimilar metals when they are joined together in a suitable electrolyte, such as a moist or aqueous environment, or soils containing moisture		N/A	All metals with the exception of most noble metals	Less difference in Galvanic series	Three conditions must be met: Electrolyte, Two different materials, An electrical connection	Any unit where there is a conductive fluid and alloys are coupled, Heat exchangers, Buried pipelines, electrical transmission support towers and ship hulls	Generalized loss in thickness or may have the appearance of a crevice, groove or pitting corrosion, depending on the driving force, conductivity	Good design Coatings can be helpful, but the more noble material should be coated	Visual inspection and UT thickness gauging	Soil corrosion	The farther the alloys are apart in the table, the higher the driving force for corrosion
22	4.3.2	Atmospheric Corrosion	Occurs from moisture associated with atmospheric conditions. Marine environments and moist polluted industrial environments with airborne contaminants are most severe		Corrosion rates increase with temp. up to about 250 °F (121 °C)	Carbon steel, Low alloy steels and Copper Alloyed aluminum	N/A	Physical location (industrial, marine, rural); moisture, designs; temperature; presence of salts, Sulfur, dirt	Equipment with low temp. to allow moisture, poor condition of paint, bimetallic connections	General or localized loss in thickness, Iron oxide (red rust)	Surface preparation and proper coating application	VT and UT	Corrosion under insulation	Dry rural environments cause very little corrosion
23	4.3.3	Corrosion Under Insulation (CUI)	Corrosion of piping, pressure vessels and structural components resulting from water trapped under insulation or fireproofing		10 (-12) to 350 (175) for CS & LAS 140 (60) to 400 (205) for SS (Aus., Dup.)	Carbon steel, low alloy steels, 300 Series SS, and duplex stainless steels	N/A	Design of insulation system, insulation type, temperature and environment	Vapor barriers, weatherproofing or mastic, at insulation termination points such as flanges, Deadlegs, supports	Localized pitting or thickness loss, Carbuncle type pitting	Appropriate paints/coatings and maintaining the insulation/sealing/vapor barriers to prevent moisture ingress	VT, UT: thickness, Profile RT: Small Bore piping, Neutron backscatter: wet insulation, Deep penetrating eddy-current, IR thermography Guided wave UT	Atmospheric corrosion, oxidation and chloride SCC	Corrosion becomes more severe at metal temp. between the boiling point 212°F (100°C) and 350°F (121°C)

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24	4.3.4	Cooling Water Corrosion	Caused by dissolved salts, gases, organic compounds or microbiological activity		Fresh water: >60 °C Brackish & Salt water: >46 °C scaling potential exists	Carbon steel, all grades of stainless steel, copper, aluminum, titanium and nickel base alloys	N/A	Temperature, type of water (fresh, brackish, salt water) and the type of cooling system, oxygen content, and velocities	Water-cooled heat exchangers and cooling towers in all applications across all industries	General corrosion, pitting corrosion, MIC, stress corrosion cracking and fouling	Proper design, operation and chemical treatment	Periodic calculation of U-factors, Ultrasonic flow meters, EC or IRIS inspection of tubes	MIC, CSCC, Galvanic corrosion	Velocities below about 3 fps (1 m/s) are likely to result in fouling
25	4.3.5	Boiler Water Condensate Corrosion	General corrosion and pitting in the boiler system and condensate return piping		N/A	Carbon steel, some low alloy steel, some 300 Series SS and copper based alloys	N/A	Dissolved gas (oxygen and or carbon dioxide), pH, temp., quality of the feedwater, and the specific feedwater treating system	external treatment system, deaerating equipment, feedwater lines, pumps, stage heaters and economizers as well as the steam generation system on both the water and fire sides and the condensate return system	O ₂ corrosion (closed heaters and economizers) tends to be a pitting. CO ₂ corrosion (condensate return) tends to be a "smooth grooving"	O ₂ scavenging treatments: sodium sulfite or hydrazine CO ₂ : Fe ₃ O ₄ or amine inhibitor	Water analysis: pH, conductivity, chlorine or residual biocide, TDS	CO ₂ corrosion, Corrosion fatigue, Erosion/erosion-corrosion	Dissolved gases, oxygen and carbon dioxide, which lead to oxygen pitting corrosion and carbonic acid corrosion respectively
26	4.3.6	CO ₂ Corrosion	When CO ₂ dissolves in water to form carbonic acid (H ₂ CO ₃). The acid may lower the pH and sufficient quantities may promote general corrosion and/or pitting corrosion of carbon steel	Corrosion occurs in the liquid phase, often at locations where CO ₂ condenses from the vapor phase		Carbon steel and low alloy steels	Cr ≥ 12%, 300 Series SS, 400 Series SS and duplex SS	Partial pressure of CO ₂ , pH and temperature	Boiler feedwater and condensate systems, Overhead systems of regenerators in CO ₂ removal plants	Localized thinning and/or pitting, Deep pitting and grooving in areas of turbulence	Corrosion inhibitors, pH above 6, Operating conditions to be maintained	General or local loss: VT, UT and RT, Weld seams: Angle probe UT or RT, Water analyses (pH, Fe, etc.)	Boiler water condensate corrosion and Carbonate cracking	Increasing partial pressures of CO ₂ result in lower pH condensate and higher rates of corrosion.
27	4.3.7	Flue-Gas Dew-Point Corrosion	SO ₂ , SO ₃ , HCl gases and the water vapor in the flue gas will condense to form sulfurous acid, sulfuric acid and hydrochloric acid which can lead to severe corrosion		Low temperatures	Carbon steel, low alloy steels and 300 Series SS	N/A	Concentration of sulfur and chlorides, operating temperature	All fired process heaters and boilers that burn fuels containing sulfur, Heat-Recovery Steam Generators (HRSG's)	H ₂ SO ₄ corrosion: Broad, shallow pits, SSC will have surface breaking cracks like crazed	Maintain Temp. above dewpoint of H ₂ SO ₄	Wall-thickness by UT, SCC of 300 Series SS using VT & PT	HCl corrosion, Chloride stress corrosion cracking	Dewpoint: H ₂ SO ₄ 280°F (138°C) HCl 130°F (54°C)
28	4.3.8	Microbiologically Induced Corrosion (MIC)	caused by living organisms such as bacteria, algae or fungi. It is often associated with the presence of tubercles or slimy organic substances		0 - 235 °F (-17 to 113 °C)	Carbon and low alloy steels, 300 Series SS and 400 Series SS, aluminum, copper and some nickel base alloys	N/A	Stagnant water or low-flow, oxygen, light or dark, high salinity, pH range of 0 to 12, temperature	MIC is most often found in heat exchangers, bottom water of storage tanks, piping with stagnant or low flow, and piping in contact with some soils, Fire water systems	Localized pitting under deposits or tubercles, Cup-shaped pits within pits in carbon steel or subsurface cavities in stainless ste	Biocides such as chlorine, bromine, ozone, UV light. Minimize low flow or stagnant zones	Measuring biocide residual, microbe counts and visual appearance, loss of duty of a heat exchanger, Foul smelling water	Cooling water corrosion	All organisms require a source of carbon, nitrogen and phosphorous for growth
29	4.3.9	Soil Corrosion	Deterioration of metals exposed to soils is referred to as soil corrosion		N/A	Carbon steel, cast iron and ductile iron	N/A	Temp., moisture and oxygen availability, soil resistivity, soil type, cathodic protection, stray current drainage, coating type, age	Underground piping and equipment as well as buried tanks and the bottoms of above ground storage tanks, Ground supported metal structures	External thinning with localized losses due to pitting	Use of special backfill, coatings and cathodic protection	The structure to soil potential, inline inspection devices, guided UT tools, indirectly by pressure testing, or visually by evaluation	Galvanic corrosion	The most effective protection is a combination of a corrosion resistant coating and a cathodic protection system
30	4.3.10	Caustic Corrosion	Localized corrosion due to the concentration of caustic or alkaline salts that usually occurs under evaporative or high heat transfer conditions		Above 150 °F (66 °C)	Carbon steel, low alloy steels and 300 Series SS	400 and some Nickel base Alloys	Caustic (NaOH or KOH)	Boilers and steam generating equipment including heat exchangers, preheat exchangers, furnace tubes and transfer lines	localized metal loss as grooves or locally thinned areas under insulating deposits	Proper design, Reducing the amount of free caustic, Adequate water flooding	UT Thickness gauging, UT scans and radiography, Injection points inspection, visual inspection with the use a boroscope	Also referred to as caustic gouging or ductile gouging	Very high corrosion rates above 200°F (93°C)
31	4.3.11	Dealloying	One or more constituents of an alloy are preferentially attacked leaving a lower density (dealloyed) often porous structure	Mechanical properties of the dealloyed material are significantly degraded		Copper alloys (brass, bronze, tin) as well as Alloy 400 and cast iron	N/A	Composition of the alloy and exposure conditions including temperature, degree of aeration, pH and exposure time	Underground cast iron piping, Heat exchanger tubing (brass, Al brass), Boiler feedwater piping systems and after boiler components	Color change or a deep etched (corroded) appearance, Uniform through the cross-section (layer-type) or it can be localized (plug-type)	Addition of certain alloying elements to resist dealloying. Altering the exposure conditions	Color change, Metallography, Acoustic techniques (loss of "metallic ring") and ultrasonic attenuation, Fitness-For-Service (FFS)	Dezincification, Destannification, Denickelification, Dealumination, Graphitic corrosion, Selective leaching	Dealloying in brasses is visually evident by a reddish, copper color instead of the yellow brass color
32	4.3.12	Graphitic Corrosion	Dealloying in which the iron matrix is corroded, leaving corrosion products and porous graphite	Loss of strength, ductility and density		Gray cast iron, nodular and malleable cast irons	White iron is not subject to this damage because there is no free graphite	Temperature, moisture, degree of aeration, low pH and exposure time	soft water, salt water, mine waters, dilute acids and in underground piping, as well as in boiler feedwater equipment, Fire water system	Widespread or localized, may not be noticeable VT. Damaged areas will be soft and easily gouged with a knife or hand tools	Internal GC: coatings and/or cement linings External GC: external coatings or cathodic protection	Acoustic techniques (loss of "metallic ring") and ultrasonic attenuation, Hardness test	Selective leaching, Dealloying	Cast irons are comprised of graphite particles embedded in an iron matrix. Graphitic corrosion may affect adjacent components by causing galvanic corrosion
4.4 High Temperature Corrosion (>400°F (204°C))														
33	4.4.1	Oxidation	Oxygen reacts with carbon steel and other alloys at high temperature converting the metal to oxide scale		Significant at 1000 °F (538 °C)	carbon steel and low alloy steels, 300 Series SS, 400 Series SS and nickel base alloys	Chromium content of the material	Metal temperature and alloy composition	Fired heaters and boilers, combustion equipment, piping and equipment that operates in high temperature environments when metal temperatures exceed about 1000°F (538°C)	CS and Alloys: General thinning 300 Series SS and nickel alloys: Generally have a very thin dark scale	Upgrading to a more resistant alloy, Chromium is the primary alloying element that affects resistance to oxidation	Operating conditions monitoring, tubekin thermocouples and/or infrared thermography, External ultrasonic thickness measurements	N/A	Rates of metal loss increase with increasing temperature
34	4.4.2	Sulfidation	Corrosion of carbon steel and other alloys resulting from their reaction with sulfur compounds in high temperature environments. The presence of hydrogen accelerates corrosion. This mechanism is also known as sulfidic corrosion		Begins at metal temperatures above 500 °F (260 °C)	Carbon steel and low alloy steels, 300 Series SS and 400 Series SS, Nickel base alloys, Copper base alloys	Chromium content of the material	Composition, temperature and concentration of corrosive sulfur compounds.	Crude, FCC, coker, vacuum, visbreaker and hydroprocessing units Heaters fired with oil, gas, coke, Boilers and high temperature equipment	Uniform thinning but can also occur as localized corrosion or high velocity erosion-corrosion damage, A sulfide scale will cover the surface of components	Upgrading to a higher chromium alloy, solid or clad 300 or 400 Series SS	Operating conditions monitoring for sulfur level, tubekin thermocouples and/or infrared thermography, External ultrasonic thickness measurements, Proactive and retroactive PMI	Sulfidic corrosion	Sulfide scale on the surface of the component offers varying degrees of protection depending on the alloy and the severity of the process stream
35	4.4.3	Carburization	Carbon is absorbed into a material at elevated temp. while in contact with a carbonaceous material or carburizing environment	Loss of high temp. creep ductility, loss of ambient temp. mechanical properties, loss of weldability, and corrosion resistance		Carbon steel and low alloy steels, 300 & 400 Series SS, cast stainless steels, nickel base alloys (e.g., Alloys 600 and 800) and HK/HP alloys.	Chromium content of the material	Carburizing environment, High temp., Susceptible material, High gas phase carbon activity and low oxygen potential	Fired heater tubes, Coke deposits, Ethylene pyrolysis and steam reformer furnaces	Substantial increases in hardness and loss in ductility, Volumetric increase, increase in level of ferromagnetism	Select alloys strong surface oxide or sulfide film formers, Reduce the carbon activity through lower temp. and higher oxygen/sulfur partial pressures	Hardness testing and field metallography, Cracking: RT, UT and some magnetic techniques	A severe form of carburization known as metal dusting	Sulfur inhibits carburization and is often added in the process stream in small amounts in steam/gas cracking in olefin and thermal hydroalkylation units
36	4.4.4	Decarburization	The removal of carbon and carbides leaving only an iron matrix	Loss of room temp. tensile strength and creep strength		Carbon steels and low alloy steels	Chromium and Molybdenum contents of the material	Time, temperature and low carbon activity	Hydroprocessing or catalytic reforming units, well as fired heater tubes,	Damage occurs on the surface exposed to the gas environment. The decarburized layer will be free of carbide phases. Carbon steel will be pure iron	By controlling the chemistry of the gas phase and alloy selection, Alloy steels with Cr and Mo are more resistant	Field Metallography and Replication (FMR), Decarburization results in a softening that can be confirmed by hardness testing	High Temperature Hydrogen Attack (HTHA)	Shallow decarburization can slightly decrease the strength of the material, but has no detrimental effect on the overall performance of the component

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37	4.4.5	Metal Dusting	Form of carburization resulting in accelerated localized pitting which occurs in carburizing gases and/or process streams containing carbon and hydrogen. Pits usually form on the surface and may contain soot or graphite dust		900 to 1500 °F (482 to 816 °C)	Low alloy steels, 300 Series SS, nickel base alloys and heat resisting alloys	There is currently no known metal alloy that is immune to metal dusting under all conditions	Process stream composition, operating temperature and alloy composition	fired heater tubes, thermowells and furnace components, catalytic reforming unit heater tubes, coker heaters, gas turbines, methanol reforming unit outlet piping	LAS: small pits filled with a crumbly residue of metal oxides and carbides SS & HAS: local, appearing as deep, round pits	Addition of Sulfur to form protective sulfide layer, Aluminum diffusion treatment	Compression wave ultrasonic testing, RT techniques can be employed to look for pitting and wall thinning. VT if accessible, Filtering cooled furnace effluent	Catastrophic carburization	
38	4.4.6	Fuel Ash Corrosion	High temperature wastage of materials that occurs when contaminants in the fuel form deposits and melt on the metal surfaces of fired heaters, boilers and gas turbines. The resulting molten salts (slags) dissolve the surface oxide and enhance the transport of oxygen to the surface to re-form the iron oxide at the expense of the tube wall or component.		Below the Melting Point of contaminant	All conventional alloys used for process heater and boiler	Alloys of the 50Cr-50Ni family	Concentration of molten salt forming contaminants, metal temperature and alloy composition	Fired heater or gas turbine utilizing fuels with the aforementioned contaminants.	Severe metal loss associated with slugging, "alligator-hide appearance"	Blending or changing fuel sources, Proper burner design and burner management, injecting special additives into the fuel	Visual inspection, Tubes need to be grit blasted in order to remove the tenacious glass-like ash deposit. UT examination may be useful to measure loss of thickness.	Hot corrosion, hot ash corrosion, molten salt corrosion, oil ash corrosion and coal ash corrosion are used to describe this mechanism	Corrosion typically occurs with fuel oil or coal that is contaminated with a combination of sulfur, sodium, potassium and/or vanadium
39	4.4.7	Nitriding	A hard, brittle surface layer will develop on some alloys due to exposure to high temp. process streams containing high levels of nitrogen compounds such as ammonia or cyanides, particularly under reducing conditions	A loss of high temperature creep strength, ambient temperature mechanical properties (specifically toughness/ductility), weldability and corrosion resistance may result	Above 600 °F (316 °C) and becomes severe above 900 °F (482 °F)	Carbon steels, low alloy steels, 300 Series SS and 400 Series SS	Nickel base alloys are more resistant	Temperature, time, partial pressure of nitrogen and metal composition.	Methane-reformers, steam gas cracking (olefin plants) and ammonia synthesis plants	Dull, dark gray appearance. Very high surface hardness, needle-like particles of iron nitrides (Fe ₃ N or Fe ₄ N)	Changing to more resistant alloys with 30% to 80% nickel,	A change in surface color, Hardness testing, Metallography, EC testing, PT, RT and UT for cracking	Carburization and metal dusting	Nitrided layers are magnetic
4.5 Environment – Assisted Cracking														
40	4.5.1	Chloride Stress Corrosion Cracking (Cl-SCC)	Surface initiated cracks caused by environmental cracking under the combined action of tensile stress, temperature and an aqueous chloride environment. The presence of dissolved oxygen increases propensity for cracking.		Above 140 °F (60 °C)	All 300 Series SS highly susceptible, Duplex stainless steels more resistant.	Nickel base alloys, Carbon steels, low alloy steels and 400 Series SS	Chloride content, pH, temp., stress, presence of oxygen and alloy composition	All 300 Series SS piping and pressure vessel components, Cracking in water-cooled condensers and in crude tower overhead condensers, Drains in hydroprocessing units, Bellows and instrument tubing, Cracking in boiler drain lines	Surface breaking cracks process side or externally under insulation, branches and craze-cracked, branched transgranular cracks, brittle appearance	resistant materials of construction, use low chloride content water for hydrotest, avoid stagnation of chlorides, PWHT	Visually, PT or phase analysis EC techniques are the preferred methods, UT, RT is not sufficiently sensitive to detect cracks except in advanced stages	Caustic SCC and polythionic acid SCC	Increasing temperatures increase the susceptibility to cracking, SCC usually occurs at pH > 2. External Cl-SCC has also been a problem on insulated surfaces when insulation gets wet
41	4.5.2	Corrosion Fatigue	Form of fatigue cracking in which cracks develop under the combined effects of cyclic loading and corrosion. Cracking often initiates at a stress concentration such as a pit in the surface. Cracking can initiate at multiple sites		N/A	All metals and alloys	N/A	Material, corrosive environment, cyclic stresses and stress raisers	i. Rotating Equipment ii. Deaerators iii. Cyclic Boilers	Fracture is brittle and the cracks are most often transgranular, multiple parallel cracks	More corrosion resistant materials, PWHT, grinding weld contours smooth, minimize the differential expansion strains	Cracks: UT, MT, WFMT, EMATS techniques	Mechanical fatigue, vibration induced fatigue	Crack initiation sites include concentrators such as pits, notches, surface defects, changes in section or fillet welds
42	4.5.3	Caustic Stress Corrosion Cracking (Caustic Embrittlement)	surface-initiated cracks that occur in piping and equipment exposed to caustic, primarily adjacent to non-PWHT'd welds		N/A	Carbon steel, low alloy steels and 300 Series SS	Nickel base alloys	Caustic strength, metal temperature and stress levels	Piping and equipment that handles caustic, including H ₂ S and mercaptan removal units,	Propagates parallel to the weld in adjacent base metal, spider web of small cracks, Cracking in 300 SS is transgranular	PWHT of CS: 1150°F (621°C), low-pressure steam for steam out, Proper design and operation of the injection system	Cracks: WFMT, EC, RT or ACFM techniques Crack depth: UT, external SWUT Crack growth: AET PT and RT for suitable for finding tight cracks	Amine cracking and carbonate cracking	Increasing caustic conc. and increasing temp. increase the likelihood and severity of cracking, caustic conc. of 50 to 100 ppm are sufficient to cause cracking
43	4.5.4	Ammonia Stress Corrosion Cracking	Aqueous streams containing ammonia may cause Stress Corrosion Cracking (SCC) in some copper alloys		Any temperature	Copper alloys in aqueous ammonia and/or ammonium compounds	90-10CuNi and 70-30CuNi, 300 Series SS and nickel base alloys are immune	Copper: Residual stress, chemical compound, pH >8.5, oxygen, Zinc content > 15%	Copper-zinc alloy tubes in heat exchangers,	Copper: Surface breaking cracks with bluish corrosion products, cracks are either transgranular or intergranular	Zinc content <15%, preventing the ingress of air	Monitor pH and ammonia of water draw samples, tubes for cracking using EC or visual inspection. Rolled area is highly susceptible.	N/A	
			Carbon steel is susceptible to SCC in anhydrous ammonia	In Steel Cracking has been reported as low as -27 °F (-33 °C) in laboratory testing	Carbon steel in anhydrous ammonia	N/A	Steel: Anhydrous ammonia with <0.2% water, air or oxygen, High residual stresses	Ammonia storage tanks, piping and equipment in ammonia refrigeration units as well as some lube oil refining processes	Cracking will occur at exposed non-PWHT welds and heat-affected zones, Cracking is primarily intergranular	Add water to the NH ₃ (0.2% min.), effective PWHT, Use LS steels (<70 ksi), Weld hardness < 225 BHN	WFMT welds inside tanks, external UT shear wave inspection using TOFD, AET	Low levels of oxygen (< 10 ppm) have been reported to lead to cracking under some conditions		
44	4.5.5	Liquid Metal Embrittlement (LME)	Cracking that results when certain molten metals come in contact with specific alloys	Cracking can be very sudden and brittle in nature	N/A	Carbon steel, low alloy steels, high strength steels, 300 Series SS, nickel base alloys and the copper alloys, aluminum alloys and titanium alloys	N/A	Metals in contact with low melting point metals such as zinc, mercury, cadmium, lead, copper and tin. High tensile stress	Melted zinc galvanizing, cadmium electrical housings, tin or lead from solders. Alloy 400, titanium or aluminum exchanger components.	Brittle cracks	Protecting metal substrates from coming into contact with the low melting metal, e.g. galvanized steel components should not be welded to 300 Series SS	MT examination for ferritic steel and PT examination for 300 Series SS and nickel base alloys. RT for exchanger pipes due to high density of Mercury	Also know as Liquid Metal Cracking (LMC)	Once cracking from LME has initiated, grinding out the affected area is not an acceptable fix
45	4.5.6	Hydrogen Embrittlement (HE)	Penetration of atomic hydrogen can lead to brittle cracking. It can occur during manufacturing, welding	A loss in ductility of high strength	Ambient to about 300°F (149°C). Effects decrease with increasing temp.	Carbon steel and low alloy steels, 400 Series SS, Precipitation Hardenable (PH) SS and some high strength nickel base alloys	As strength increases, susceptibility to HE increases.	Hydrogen conc. within the steel, strength and micro structure of steel, stress above the threshold	Piping and vessels in wet H ₂ S services in FCC, hydroprocessing, amine, sour water services, Storage spheres, Bolts and springs made of HS steel, Cr-Mo reactors, drums and exchanger shells in hydroprocessing	Initiate sub-surface cracking, cracking is often intergranular	Use LS steels and PWHT to temper the microstructure, improve ductility and reduce residual stresses and hardness. Apply a protective lining, SS cladding or weld overlay	Surface cracking inspection use PT, MT or WFMT. UT may also be useful in finding HE cracks. RT often is not sufficiently sensitive to detect HE cracks	Also know as Hydrogen flaking, underbead cracking, delayed cracking, hydrogen assisted cracking	It can also occur or from services that can charge hydrogen into the steel in an aqueous, corrosive, or a gaseous environment
46	4.5.7	Ethanol Stress Corrosion Cracking (SCC)	Surface-initiated cracks caused by environmental cracking of carbon steel under the combined action of tensile stress and a fuel grade ethanol (FGE, ASTM D 4806) or FGE / gasoline blend environment		N/A	All grades of carbon steel, Alloys of aluminum, copper and copper alloys, lead and zinc	Other than Carbon Steel and Al, Cu, Pb, Zn Alloys	High Stress, dissolved oxygen content, water content between 0.1 and 4.5 vol%, FGE and gasoline containing as little as 20 vol% FGE	Carbon steel storage tanks, rack piping, and associated equipment, pipeline used to transport FGE,	Cracks parallel to the weld or transverse to the weld, Cracks are branched and intergranular, but also transgranular	PWHT or by applying coatings, Avoid the usage of lap seam welds, Minimize cold working during fabrication, Avoid designs with highly localized tensile stresses	Methods for ethanol SCC inspection are similar as for other types of SCC e.g. WFMT, SWUT, ACFM. EC is unproven as a method for detection of ethanol SCC	Ethanol SCC is assumed to be similar to other reported in methanol and various alkaline aqueous solutions	Dissolved oxygen and the presence of variable stresses such as cyclic stress or component flexing, increase the propensity for cracking
47	4.5.8	Sulfate Stress Corrosion Cracking	Surface initiated cracks caused by environmental cracking of copper alloys in sulfate solutions over many years.		N/A	Some copper alloys	The 90/10 and 70/30 copper nickel alloys are more resistant. Non-copper based alloys are immune	Stress levels, Sulfate chemical compounds,	Tubes in heat exchanger bundles in overhead distillation systems,	Tubes show single or highly branched cracks on the surface. Transgranular cracks. Slow leaks as opposed to tube rupture	Periodic cleaning once every five years, Use 90-10CuNi and 70-30CuNi alloys	Heat exchanger tubes for cracking using EC or visual inspection. Physical bending of sample tubes	N/A	Cracking usually occurs over a period of many years, sometimes taking as long as 10 to 15 years to cause tube leaks.
Refining Industry Damage Mechanism														

Sr #	Sec.	Damage Mechanism	Definition	Defect	Temperature °F (°C)	Affected Materials	Resistant Materials	Critical Factors	Affected Units /Equipment	Morphology	Mitigation	Inspection	Related Mechanism	Comments	
	5.1.1	Uniform or Localized Loss in Thickness Phenomena													
48	5.1.1.1	Amine Corrosion	Occurs principally on carbon steel in amine treating processes. Corrosion is not caused by the amine itself, but results from dissolved acid gases (CO ₂ and H ₂ S), amine degradation products, Heat Stable Amine Salts (HSAS) and other contaminants. Corrosion rates increase with increasing temperature.		Temperatures above about 220°F (104°C) can result in acid gas flashing	Carbon steel	300 Series SS	Design and operating practices, the type of amine, amine concentration, contaminants, temperature and velocity.	Crude, coker, FCC, hydrogen reforming, hydroprocessing, and tail gas units, regenerator reboller and the regenerator, lean/rich exchangers	Carbon steel and low alloy steels uniform thinning, localized corrosion or localized underdeposit attack	Proper operation, upgrading to 300 Series SS or other corrosion resistant alloys	Visual examination and UT thickness measurement, UT scans or profile radiography are used for external inspection. Corrosion monitoring	Amine stress corrosion cracking	Aggressiveness from most to least as follows: (MEA), (DGA), (DIPA), (DEA), (MDEA). For CS, velocity limits are limited to 3 to 6 fps for rich amine and about 20 fps for lean amine	
49	5.1.1.2	Ammonium Bisulfide Corrosion (Alkaline Sour Water)	Aggressive corrosion occurring in hydroprocessing reactor effluent streams and in units handling alkaline sour water		120 -150°F (49 - 66°C)	Carbon steel is less resistant	300 Series SS, duplex SS, aluminum alloys and nickel base alloys are more resistant	NH ₄ HS concentration, H ₂ S partial pressure, velocity and/or localized turbulence, pH, temperature, Alloy composition and flow distribution	Hydroprocessing Units, FCC Units, Sour Water Strippers (SWS), Amine Units, Delayed Coker	General loss in thickness, localized under-deposit corrosion	Good design practices, Maintain velocities within industry guidelines of 10 to 20 fps for carbon steel. Use Alloy e.g 825, duplex SS at velocities above 20 fps	Sampling and calculation bisulfide, UT scanning and/or RT profile thickness of high and low velocity areas, UT downstream of control valves, IRIS, RFEC and flux leakage steel air cooler tubes, EC inspect non-magnetic air cooler tubes	Erosion/erosion corrosion	Above 2 wt % NH₄HS, solutions are increasingly corrosive	
50	5.1.1.3	Ammonium Chloride Corrosion	Normally occurring under ammonium chloride or amine salt deposits, often in the absence of a free water phase		Well above the water dewpoint (> 300°F (149°C))	Increasing Resistance: Carbon steel < low alloy steels < 300 Series SS < Alloys 400 < duplex SS, 800, and 825 < Alloys 625, C276 < titanium		Concentration (NH ₃ , HCl, H ₂ O or amine salts), temperature and water availability	Crude Tower Overheads, Hydroprocessing, Catalytic Reforming, FCCU and coker fractionator overheads	Salts have a whitish, greenish or brownish appearance, very localized and results in pitting	Use of Filming amine inhibitors, Limit chlorides, water wash may be required	RT or UT thickness monitoring, Corrosion probes or coupons can be useful	HCl corrosion, Chloride SCC		
51	5.1.1.4	Hydrochloric Acid (HCl) Corrosion	Aqueous HCl causes both general and localized corrosion and is very aggressive to most common materials of construction across a wide range of concentrations. The first water droplets that condense can be highly acidic (low pH) and promote high corrosion rates.		N/A	All common materials of construction used in refineries	Alloy 400, titanium and some other nickel base alloys have good resistance to dilute HCl acid in many refinery application	HCl acid concentration, temperature and alloy composition. The severity of corrosion increases with increasing HCl concentration and increasing temperature	Crude Unit, Hydroprocessing Units, Catalytic Reforming Units	CS & LAS: uniform thinning, localized corrosion or underdeposit attack. 300 SS & 400 SS: pitting 300 SS: may experience chloride SCC	Reduce chloride in the feed, Use nickel base alloys or titanium, Minimize carryover of water and chloride salts,	General thinning but may be highly localized,	Ammonium chloride corrosion, Chloride SCC	Carbon steel and low alloy steels are subject to excessive corrosion when exposed to any concentration of HCl acid that produces at pH below about 4.5	
52	5.1.1.5	High Temp H₂/H₂S Corrosion	Presence of hydrogen in H ₂ S-containing hydrocarbon streams increases the severity of high temperature sulfide corrosion		Above about 500°F (260°C)	Increasing resistance: Carbon steel < low alloy steels < 400 Series SS < 300 Series SS		Hydrogen, the concentration of H ₂ S and the alloy composition	Hydroprocessing units such desulfurizers, hydrotreaters and hydrocracking units	Uniform loss in thickness from the process side and is accompanied by the formation of an iron sulfide scale	Use alloys with high chromium content	UT, VT and RT thickness readings	High temperature sulfidation	Scale is about 5 times the volume of lost metal and may be in multiple layers. Tightly adherent shiny gray scale attached to the surface may be mistaken for unaffected metal	
53	5.1.1.6	Hydrofluoric (HF) Acid Corrosion	Corrosion by HF acid can result in high rates of general or localized corrosion and may be accompanied by hydrogen cracking, blistering and/or HIC/SOHIC		Above 150 °F (66 °C)	Carbon steel, copper-nickel alloys, Alloy 400	Alloy C276 has been used where there have been cracking problems with Alloy 400	HF acid concentration (water content), temperature, alloy composition and the presence of contaminants including oxygen and sulfur compounds	HF alkylation unit, flare piping and downstream units, Isostrripper and Depropanizer towers	Localized general or severe thinning of CS	Careful operation of the unit to minimize water, oxygen, sulfur. Alloy 400 (solid or clad) can be used to eliminate the problems associated with blistering and HIC/SOHIC	UT and RT for thickness monitoring	Environmental cracking, Hydrogen stress cracking in HF	Low alloy steels, 300 Series SS and the 400 Series SS are susceptible to corrosion and/or cracking and are generally not suitable for HF service	
54	5.1.1.7	Naphthenic Acid Corrosion (NAC)	A form of high temperature corrosion that occurs primarily in crude and vacuum units, and downstream units that process certain fractions or cuts that contain naphthenic acids.		N/A	Carbon steel, low alloy steels, 300 Series SS, 400 Series SS and nickel base alloys	Alloys containing increasing amounts of molybdenum show improved resistance	naphthenic acid content (neutralization number), TAN's as low as 0.10, temperature, sulfur content, velocity and alloy composition	Crude and vacuum heater tubes, crude and vacuum transfer lines; vacuum bottoms piping, AGO circuits; HVGO	Localized corrosion, pitting corrosion, or flow induced grooving	Use alloys with higher molybdenum content for improved resistance. NAC can be reduced by blending crude to reduce the TAN and/or increase the sulfur content	UT and RT are used for thickness, Monitor TAN and sulfur content, Hydrogen probes, Electrical resistance corrosion probes and corrosion coupon racks	In cases where thinning is occurring, it is difficult to distinguish between NAC and sulfidation.	It is most severe in two phase (liquid and vapor) flow, in areas of high velocity or turbulence, and in distillation towers where hot vapors condense to form liquid	
55	5.1.1.8	Phenol (Carbolic Acid) Corrosion	Corrosion of carbon steel can occur in plants using phenol as a solvent to remove aromatic compounds from lubricating oil feedstocks.		Above 250°F (121 °C)	Increasing resistance: Carbon steel < 304L < 316L < Alloy C276		Temperature, water content, alloy chemistry and velocity	Phenol extraction facilities in lubes plant	General or localized corrosion of carbon steel	Proper materials selection and control of phenol solvent chemistry. Type 316L SS to be used, Alloy C276 has been used in areas of high velocity	UT and RT to monitor for loss in thickness. ER corrosion probes and corrosion coupons have been used for corrosion monitoring	N/A	Maximum velocity of 30 fps in the recovery section. Temp. should be maintained to at least 30°F (17°C) above the dewpoint	
56	5.1.1.9	Phosphoric Acid Corrosion	Phosphoric acid is most often used as a catalyst in polymerization units. It can cause both pitting corrosion and localized corrosion of carbon steels depending on water content.		Corrosion rates increase with increasing temp.	Increasing resistance: Carbon steel < 304L < 316L < Alloy 20		Acid concentration, temperature and contaminants	Piping and equipment in the polymerization unit where water mixes with catalyst. Low velocity areas like piping manifolds, the bottom of kettle-type reboilers, partial penetration welds, and exchangers	General or localized thinning of carbon steel	304L is satisfactory for up to about 120°F (49°C) . Type 316L SS is required from 120°F to 225°F (49°C to 107°C) . 316L SS and Alloy 20 are effective at concentrations up to 85% at boiling temp.	UT and RT for loss of thickness. Sample iron in water from first column overhead receiver. ER probes and/or corrosion coupons.	N/A	Most corrosion probably occurs during water washing operations at shutdowns. Contaminants, such as chlorides, can increase phosphoric acid corrosion	
57	5.1.1.10	Sour Water Corrosion (Acidic)	Corrosion of steel due to acidic sour water containing H ₂ S at a pH between 4.5 and 7.0 . Carbon dioxide (CO ₂) may also be present.		N/A	Carbon Steel	Stainless steels, copper alloys and nickel base alloys	H ₂ S content, pH, temperature, velocity and oxygen concentration	Acid sour water corrosion is a concern in overhead systems of FCC and coker gas fractionation plants with high H ₂ S levels and low NH ₃ levels.	General thinning. However, localized corrosion or localized underdeposit attack can occur, especially if oxygen is present.	Copper alloys and nickel alloys are generally not susceptible to acid sour water corrosion. However, copper alloys are vulnerable to corrosion in environments with ammonia.	Scanning ultrasonic thickness methods or profile radiography. Periodic measurement of pH. Properly placed corrosion probes and corrosion coupons	Wet H ₂ S damage, Carbonate SCC	H₂S concentration in the sour water decreases as temp. increases. Above a pH of 4.5, a protective, thin iron sulfide layer limits the corrosion rate.	
58	5.1.1.11	Sulfuric Acid Corrosion	Sulfuric acid promotes general and localized corrosion of carbon steel and other alloys. Carbon steel heat affected zones may experience severe corrosion		N/A	Increasing resistance: Carbon steel < 316L < Alloy 20 high silicon cast iron < high nickel cast iron < Alloy B-2 < Alloy C276		Acid concentration, temperature, alloy content, velocity, contamination and presence of oxidizers	Sulfuric acid alkylation units and waste water treatment plants	General in nature, but attacks carbon steel weld heat affected zones, Hydrogen grooving may occur, Sulfuric acid attacks slag left from welding	Materials selection and proper operation within design velocities, Caustic to neutralize the acid	UT or RT inspection of turbulent zones and hottest areas. Corrosion monitoring with coupons and ER probes	N/A	Carbon steel corrosion rates increase significantly if the flow velocity exceeds about 2 to 3 fps (0.6 to 0.9 m/s) or at acid concentrations below 65% .	

Sr #	Sec.	Damage Mechanism	Definition	Defect	Temperature °F (°C)	Affected Materials	Resistant Materials	Critical Factors	Affected Units /Equipment	Morphology	Mitigation	Inspection	Related Mechanism	Comments
59	5.1.1.12	Aqueous Organic Acid Corrosion	Naturally occurring acids may contribute significantly to aqueous corrosion depending on the type and quantity of acids, and the presence of other contaminants. These acids may also result from additives used in upstream operations or desalting		N/A	All grades of Carbon steel	N/A	Type and quantity of organic acids, metal temperature, fluid velocity, system pH, and presence of other acids	Carbon steel piping and process equipment in crude tower, vacuum tower and coker fractionator overhead systems including heat exchangers, towers and drums	Corroded surface smooth and damage may be difficult to distinguish. In pipe or other equipment where there is significant flow, the surfaces are sometimes smoothly grooved.	Minimized through the injection of a chemical neutralizing additive. Upgrading to corrosion-resistant alloys	UT and RT for loss of thickness. Long range UT techniques for long run pipe. Automatic ultrasonic scanning methods or profile RT for locally thinned areas. Strategically placed corrosion probes and/or corrosion coupons	HCl corrosion, Ammonium chloride corrosion	Organic compounds in the crude furnace form low molecular weight organic acids which condense in distillation tower overhead systems.
5.1.2 Environment-Assisted Cracking														
60	5.1.2.1	Polythionic Acid Stress Corrosion Cracking (PASCC)	Normally occurring during shutdowns, startups or during operation when air and moisture are present. Cracking is due to sulfur acids forming from sulfide scale, air and moisture acting on sensitized austenitic stainless steels. Usually adjacent to welds or high stress areas.		750°F to 1500°F (400°C to 815°C)	300 Series SS, Alloy 600/600H and Alloy 800/800H	N/A	A combination of environment, material, and stress	All units where sensitized alloys are used in sulfur-containing environments, commonly damaged heat exchanger tubes, furnace tubes and piping	localized and may not be evident until a leak appears during start-up. Cracking propagates intergranularly	Flushing the equipment with alkaline or soda ash solution to neutralize sulfur acids	Flapper disc sanding prior to PT,	"Sensitization" refers to the composition / time / temp. dependent formation of chromium carbide in the grain boundaries of the metal. Sensitization occurs in the 750°F to 1500°F (400°C to 815°C) temp. range.	
61	5.1.2.2	Amine Stress Corrosion Cracking	Combined action of tensile stress and corrosion in aqueous alkanol/amine systems used to remove /absorb H ₂ S and/or CO ₂ and their mixtures from various gas and liquid hydrocarbon streams. Amine cracking is most often associated with lean amine services.		N/A	Carbon steel and low alloy steels	Solid or clad stainless steel, Alloy 400	Level of tensile stress, amine concentration and temperature	All non-PWHT carbon steel piping and equipment in lean amine service including contactors, absorbers, strippers, regenerators and heat exchangers as well as any equipment subject to amine carryover.	Surface breaking flaws that initiate on the ID of piping and equipment primarily in the weld HAZ. Cracking typically develops parallel to the weld	PWHT all carbon steel welds in piping and equipment. Water wash non-PWHT carbon steel piping and equipment prior to welding, heat treatment or steamout.	WFMT or ACFM techniques, PT is usually not effective. UT technique including external SWUT. AET can also be used for monitoring crack growth and locating growing cracks	Amine cracking is more properly termed amine stress corrosion cracking	Amine cracking is a form of alkaline stress corrosion cracking. It is most often found at or adjacent to non-PWHT'd carbon steel weldments or in highly cold worked parts
62	5.1.2.3	Wet H₂S Damage (Blistering/HIC/SOHIC/SSC)	Hydrogen Blistering: Surface bulges on the ID, the OD or within the wall thickness of a pipe or pressure vessel. 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, HIC, and SOHIC. Ambient and 300°F (150°C) or higher SSC: Below about 180°F (82°C)	Carbon steel and low alloy steels	N/A	Environmental conditions (pH, H ₂ S level, contaminants, temp.), material properties (hardness, microstructure, strength) and tensile stress level. Hydrogen permeation or diffusion rates have been found to be minimal at pH 7 and increase at both higher and lower pH. Hydrogen permeation increases with increasing H ₂ S partial pressure.	Blistering, HIC, SOHIC and SSC damage can occur throughout the refinery wherever there is a wet H ₂ S environment present. In hydroprocessing units, increasing concentration of ammonium bisulfide above 2% increases the potential for blistering, HIC and SOHIC. Cyanides significantly increase the probability and severity of blistering, HIC and SOHIC damage. SSC is most likely found in hard weld and heat affected zones and in high strength components including bolts, relief valve springs, 400 Series SS valve trim, compressor shafts, sleeves and springs.	Hydrogen blisters appear as bulges on the ID or OD surface	Effective barriers that protect the surface of the steel from the wet H ₂ S environment	Process conditions should be evaluated. Inspection for wet H ₂ S damage generally focuses on weld seams and nozzles. WFMT, EC, RT or ACFM techniques. UT techniques including external SWUT. AET can be used for monitoring crack growth.	Blistering results from hydrogen generated by corrosion, not hydrogen gas from the process stream. PWHT will not prevent Blistering and HIC from occurring	
			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"	HIC damage can occur wherever blistering or subsurface laminations are present						HIC-resistant steels can be used	HIC is often found in so-called "dirty" steels with high levels of inclusions			
			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.	In pressure-containing equipment, SOHIC and SSC damage is most often associated with the weldments						Wash water injection to dilute the HCN concentration. PWHT can also help to minimize susceptibility to SOHIC. Specialized corrosion inhibitors	Blistering, HIC and SOHIC damage are not related to steel hardness. SOHIC is driven by localized stresses so that PWHT is also somewhat effective in reducing SOHIC damage.			
			Sulfide Stress Cracking (SSC): Cracking of metal under the combined action of tensile stress and corrosion in the presence of water and H ₂ 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 also be found at any location where zones of high hardness are found in vessels or in high strength steel components							SSC can initiate on the surface of steels in highly localized zones of high hardness in the weld metal and heat affected zones. Hardness is primarily an issue with SSC. PWHT is highly effective in preventing or eliminating SSC by reduction of both hardness and residual stress			
63	5.1.2.4	Hydrogen Stress Cracking - HF	Hydrogen Stress Cracking is a form of environmental cracking that can initiate on the surface of high strength low alloy steels and carbon steels with highly localized zones of high hardness in the weld metal and HAZ as a result of exposure to aqueous HF acid environments		N/A	Carbon steel and low alloy steels.	N/A	Steel hardness, strength and stress	All piping and equipment exposed to HF acid at any concentration with hardness levels above the recommended limit. ASTM A193B7M bolts are also susceptible if overtorqued	Surface breaking cracks, usually associated with weldments. Cracking will be intergranular.	PWHT is beneficial in reducing the hardness and residual stresses. Use carbon steels with Carbon Equivalents (CE) less than 0.43.	Metallography, WFMT, Hardness testing	Same mechanism that is responsible for SCC in wet H ₂ S environments except that HF acid is generating the hydrogen	Susceptibility increases with increasing hardness. Hardness levels above Rockwell C 22 (237 BHN) are highly susceptible.
64	5.1.2.5	Carbonate Stress Corrosion Cracking (ACSCC)	Surface breaking cracks that occur adjacent to carbon steel welds under the combined action of tensile stress in systems containing a free water phase with carbonate, where some amount of H ₂ S is also present		N/A	Carbon steel and low alloy steels	N/A	Residual stress level of carbon steel and the water chemistry. Most failures have occurred in the range of pH 8 to 10	Fluid catalytic cracking unit main fractionator overhead condensing and reflux system, the downstream wet gas compression system, and the sour water systems	Propagates parallel to the weld in the heat-affected zone, or adjacent base metal within 2 inches (50 mm) of the weld	Post-fabrication stress-relieving heat treatment of 1200°F to 1225°F (649°C to 663°C). A metavanadate inhibitor can be used in hot carbonate systems in CO ₂ removal units	Monitoring the pH, CO ₂ concentration of FCC sour waters. WFMT or ACFM, UT including external SWUT techniques. AET for crack growth and locating growing cracks.	Carbonate cracking	Water wash non-PWHT piping and equipment prior to steamout or heat treatment in hot carbonate systems. Grinding out the cracks is a viable method of crack depth determination
5.1.3 Other Mechanisms														

Sr #	Sec.	Damage Mechanism	Definition	Defect	Temperature °F (°C)	Affected Materials	Resistant Materials	Critical Factors	Affected Units /Equipment	Morphology	Mitigation	Inspection	Related Mechanism	Comments
65	5.1.3.1	High Temperature Hydrogen Attack (HTHA)	Results from exposure to hydrogen at elevated temperatures and pressures. The hydrogen reacts with carbides in steel to form methane (CH ₄) which cannot diffuse through the steel. The loss of carbide causes an overall loss in strength. Methane pressure builds up, forming bubbles or cavities, microfissures and fissures that may combine to form cracks. Failure can occur when the cracks reduce the load carrying ability of the pressure containing part.		N/A	Increasing resistance: Carbon steel < C-0.5Mo < Mn-0.5Mo < 1Cr-0.5Mo < 1.25Cr-0.5Mo < 2.25Cr-1Mo < 2.25Cr-1Mo-V < 3Cr-1Mo < 5Cr-0.5Mo		Temperature, hydrogen partial pressure, time and stress.	Hydroprocessing units, such as hydrotreaters (desulfurizers) and hydrocrackers, catalytic reformers, hydrogen producing units and hydrogen cleanup units, such as pressure swing absorption units. Boiler tubes in very high pressure steam service	The hydrogen/carbon reaction can cause surface decarburization of steel. The hydrogen/carbon reaction can cause surface decarburization of steel	Use alloy steels with chromium and molybdenum to increase carbide stability	Metallographic analysis. Ultrasonic techniques using a combination of velocity ratio and AUBT for finding fissuring and/or serious cracking	N/A	The incubation period is the time period during which enough damage has occurred to be measured with available inspection techniques and may vary from hours at very severe conditions to many years
66	5.1.3.2	Titanium Hydriding	metallurgical phenomenon in which hydrogen diffuses into the titanium and reacts to form an embrittling hydride phase.	complete loss of ductility with no noticeable sign of corrosion or loss in thickness.	Above 165°F (74°C)	Titanium alloys, Zirconium alloys	N/A	Metal temperature, solution chemistry and alloy composition	water strippers and amine units in the overhead condensers, heat exchanger tubes, piping and other titanium equipment. Cathodically protected equipment with protection potentials < -0.9 v SCE.	Cracking.	Titanium should not be used in known hydriding services such as amine or sour water, where the possibility of a leak is not acceptable.	Metallography, Bend test or a crush test. Specialized eddy current techniques	N/A	Above 165°F (74°C) and at a pH below 3, pH above 8 or neutral pH with high H ₂ S content