9

Process and Oil Industries Corrosion

NONDESTRUCTIVE METHODS FOR EVALUATING MATERIALS

Method	Measures or Defects	Applications	Advantages	Limitations
Acoustic emission	Crack initiation and growth rate Internal cracking in welds during cooling Boiling or cavitation Friction or wear Plastic deformation Phase transformations	Pressure vessels Stressed structures Turbine or gear boxes Fracture mechanics research Weldments Sonic signature analysis	Remote and continuous surveillance Permanent record Dynamic (rather than static) detection of cracks Portable Triangulation techniques to locate flaws	Transducers must be placed on part surface Highly ductile materials yield low amplitude emissions Part must be stressed or operating Test system noise needs to be filtered out
Acoustic-impact (tapping)	Debonded areas or delaminations in metal or nonmetal composites or laminates Cracks in turbine wheels or turbine blades Loose rivets or fasteners Crushed core	Brazed or adhesive-bonded structures Bolted or riveted assemblies Turbine blades Turbine wheels Composite structures Honeycomb assemblies	Portable Easy to operate May be automated Permanent record or positive meter readout No couplant required	Part geometry and mass influences test results impactor and probe must be repositioned to fit geometry of part Reference standards required Pulser impact rate is critical for repeatability

Method	Measures or Defects	Applications	Advantages	Limitations
Barkhausen noise analysis	Residual stresses in ferromagnetic steels	Jet engine components such as compressor blades, discs, diffuser cases	Nondestructive stress analysis Permanent record Fully automatic	Expensive Requires reference standard Need trained operator Not yet a production tool
Eddy current (100 Hz to 10 kHz)	Subsurface cracks around fastener holes in aircraft structure	Aluminum and titanium structure	Detect subsurface cracks not detectable by radiography	Part geometry Will not detect short cracks
Eddy current (10 kHz to 6 MHz)	Surface and subsurface cracks and seams Alloy content Heat treatment variations Wall thickness, coating thickness Crack depth Conductivity Permeability	Tubing Wire Ball bearings "Spot checks" on all types of surfaces Proximity gage Metal detector Metal sorting Measure conductivity in % IACS	No special operator skills required High speed, low cost Automation possible for symmetrical parts Permanent record capability for symmetrical parts No couplant or probe contact required	Conductive materials Shallow depth or penetration (thin walls only) Masked or false indications caused by sensitivity to variations, such as part geometry, lift-off Reference standards required Permeability variations
Eddy-sonic	Debonded areas in metal-core or metal-faced honey-comb structures Delaminations in metal laminates or composites Crushed core	Metal-core honey-comb Metal-faced honey-comb Conductive laminates such as boron or graphite fiber composites Bonded metal panels	Portable Simple to operate No couplant required May be automated	Specimen or part must contain conductive materials to establish eddy-current field Reference standards required Part geometry
Electric current (direct current conduction method)	Cracks Crack depth Resistivity Wall thickness Corrosion-induced wall-thinning	Metallic materials Electrically conductive materials Train rails Nuclear fuel elements Bars, plates, other shapes	Access to only one surface required Battery or dc source Portable	Edge effect Surface contamination Good surface contact required Difficult to automate Electrode spacing Reference standards required

Method	Measures or Defects	Applications	Advantages	Limitations
Electrified particle	Surface defects in nonconducting material Through-to-metal pinholes on metal-backed material Tension, compression, cyclic cracks Brittle-coating stress cracks	Glass Porcelain enamel Nonhomogeneous materials such as plastic or asphalt coatings Glass-to-metal seals	Portable Useful on materials not practical for penetrant inspection	Poor resolution on thin coatings False indications from moisture streaks or lint Atmospheric conditions High voltage discharge
Exo-electron emission	Fatigue in metals	Metals	Access to only one surface required Permanent record Quantitative	No surface films or contamination Geometry limitations Skilled technician required
Filtered particle	Cracks Porosity Differential absorption	Porous materials such as clay, carbon, powdered metals, concrete Grinding wheels High-tension insulators Sanitary ware	Colored or fluorescent particles Leaves no residue after baking part over 400 ˚F Quickly and easily applied Portable	Size and shape of particles must be selected before use Penetrating power of suspension medium is critical Particle concentration must be controlled Skin irritation
Fluoroscopy (Cinefluorography) (Kinefluorography)	Level of fill in containers Foreign objects Internal components Density variations Voids, thickness Spacing or position	Particles in liquid flow Presence of cavitation Operation of valves and switches Burning in small solid-propellant rocket motors	High-brightness images Real-time viewing Image magnification Permanent record Moving subject can be observed	Costly equipment Geometric unsharpness thick specimens Speed of event to be studied Viewing area
Holography (acoustical- liquid surface levitation)	Lack of bond Delaminations Voids Porosity Resin-rich or resin-starved areas Inclusions Density variations	Metals Plastics Composites Laminates Honeycomb structures Ceramics Biological specimens	No hologram film development required Real-time imaging provided Liquid-surface responds rapidly to ultrasonic energy	Through-transmission techniques only Object and reference beams must superimpose on special liquid surface Immersion test only Laser required

Method	Measures or Defects	Applications	Advantages	Limitations
Holography interfero-metry)	Strain Plastic deformation Cracks Debonded areas Voids and inclusions Vibration	Bonded and com-posite structures Automotive or aircraft tires Three-dimensional imaging	Surface of test object can be uneven No special surface preparations or coatings required No physical contact with test specimen	Vibration free environment is required Heavy base to dampen vibrations Difficult to identify type of flaw de-tected
Holiday detector High voltage (spark)	Integrity of coatings or linings	Defects holidays in coatings of thickness >15 mils	Portable Easy to operate	Possible damage if dielectric strength exceeded
Holiday detector Low voltage	Integrity of coatings	Defects holidays in coatings of thickness <20 mils	Portable Easy to operate	Requires contact with substrate
Infrared (radiome-ters)	Lack of bond Hot spots Heat transfer Isotherms Temperature ranges	Brazed joints Adhesive-bonded joints Metallic platings or coatings; debonded areas or thickness Electrical assem-blies Temperature monitoring	Sensitive to 1.5 ˚F temperature variation Permanent record or thermal picture Quantitative Remote sensing; need not contact part Portable	Emissivity Liquid-nitrogen-cooled detector Critical time-temperature relationship Poor resolution for thick specimens Reference stan-dards required
Leak testing	Leaks Helium Ammonia Smoke Water Air bubbles Radioactive gas Halogens	Joints: Welded Brazed Adhesive-bonded Sealed assemblies Pressure or vacu-um chambers Fuel or gas tanks	High sensitivity to extremely small, tight separations not detectable by other NDT methods Sensitivity related to method selected	Accessibility to both surfaces of part required Smeared metal or contaminants may prevent detection Cost related to sensitivity
Magnetic field	Cracks Wall thickness Hardness Coercive force Magnetic anisotropy Magnetic field Non-magnetic coating thickness on steel	Ferromagnetic materials Ship degaussing Liquid level control Treasure hunting Wall thickness of nonmetallic materials Material sorting	Measurement of magnetic material properties May be automated Easily detect magnetic objects in nonmagnetic material Portable	Permeability Reference standards required Edge-effect Probe lift-off

Method	Measures or Defects	Applications	Advantages	Limitations
Magnetic particle	Surface and slightly subsurface defects; cracks, seams, porosity, inclusions Permeability variations Extremely sensitive for locating small tight cracks	Ferromagnetic materials; bar, forgings, weldments, extrusions, etc.	Advantage over penetrant in that it indicates subsurface defects, particularly inclusions Relatively fast and low cost May be portable	Alignment of magnetic field is critical Demagnetization of parts required after tests Parts must be cleaned before and after inspection Masking by surface coatings
Magnetic perturbation	Cracks Crack depth Broken strands in steel cables Permeability effects Nonmetallic inclusions Grinding burns and cracks under chromium plating	Ferromagnetic metals Broken steel cables in reinforced concrete	May be automated Easily detects magnetic objects in nonmagnetic materials Detects subsurface defects	Requires reference standard Need trained operator Part geometry Expensive equipment
Microwave (300 MHz-300 GHz)	Cracks, holes, debonded areas, etc. in nonmetallic parts Changes in composition, degree of cure, moisture content Thickness measurement Dielectric constant Loss tangent	Reinforced plastics Chemical products Ceramics Resins Rubber Liquids Polyurethane foam Radomes	Between radio waves and infrared in the electromagnetic spectrum Portable Contact with part surface not normally required Can be automated	Will not penetrate metals Reference standards required Horn to part spacing critical Part geometry Wave interference Vibration
Mossbauer effect	Nuclear magnetic resonance in materials, most common being iron-57 Polarization of magnetic domains in steel	Detect and identify iron in specimen or sample Detect iron films on stainless steel Measure retained austenite (2 to 35%) in steels Determine nitrided surfaces on steel Interaction of domains with dislocation in ferromagnetic materials	Provide unique information about the surroundings of the iron-57 nuclei	Radiation hazard Trained engineers or physicists required Nonportable Precision equipment for vibrating source and spectrum analysis

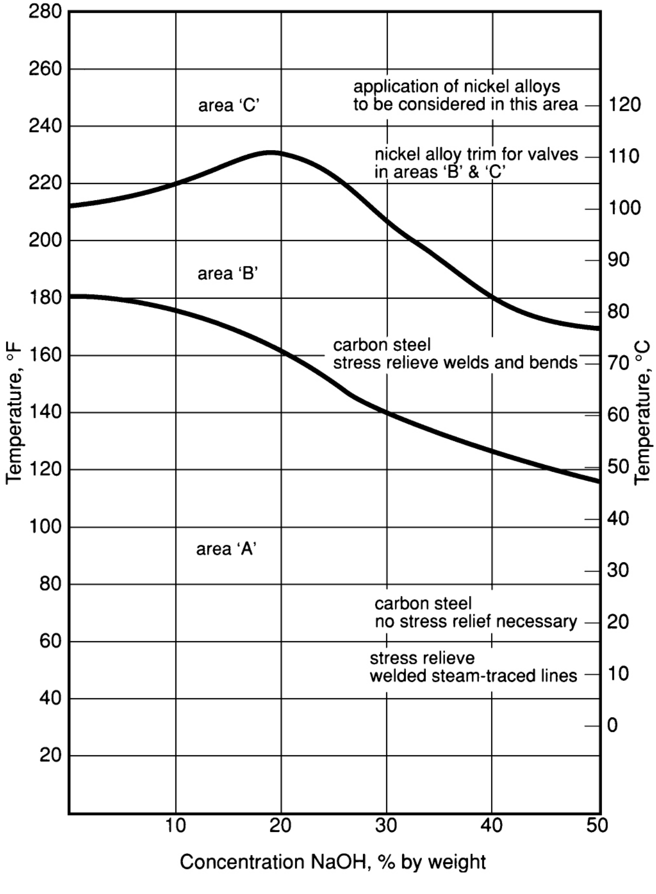
Method	Measures or Defects	Applications	Advantages	Limitations
Neutron activation analysis (Reactor, accelerator, or radioisotope)	Radiation emission resulting from neutron activation Oxygen in steel Nitrogen in food products Silicon in metals and ores	Metallurgical Prospecting Well logging Oceanography On-line process control of liquid or solid materials	Automatic systems Accurate (ppm range) Fast No contact with sample Sample preparation minimal	Radiation hazard Fast decay time Reference standard required Sensitivity varies with irradiation time
Penetrants (Dye or fluorescent)	Defects open to surface of parts: cracks, porosity, seams, laps, etc. Through-wall leaks	All parts with non-absorbing surfaces (forgings, weldments, castings, etc.) Note: Bleed-out from porous surfaces can mask indications of defects	Low cost Portable Indications may be further examined visually Results easily interpreted	Surface films, such as coatings, scale, and smeared metal may prevent detection of defects Parts must be cleaned before and after inspection Defect must be open to surface
Radiography (thermal neutrons from reactor, accelerator, or Californium 252)	Hydrogen contamination of litanium or zirconium alloys Defective or improperly loaded pyrotechnic devices Improper assembly of metal, nonmetal parts Corrosion products	Pyrotechnic devices Metallic, nonmetallic assemblies Biological specimens Nuclear reactor fuel elements and control rods Adhesive bonded structures	High neutron absorption by hydrogen, boron, lithium, cadmium, uranium, plutonium Low neutron absorption by most metals Complement to X-ray or gamma-ray radiography	Very costly equipment Nuclear reactor or accelerator required Trained physicists required Radiation hazard Nonportable Indium or gadolinium screens required
Radiography (gamma rays) Cobalt-60 Iridium-192	Internal defects and variations; porosity, inclusions, cracks, lack of fusion, geometry variations, corrosion thinning Density variations Thickness, gap and position	Usually where X-ray machines are not suitable because source cannot be placed in part with small openings and/or power source not available Panoramic imaging	Low initial cost Permanent records; film Small sources can be placed in parts with small openings Portable Low contrast	One energy level per source Source decay Radiation hazard Trained operators needed Lower image resolution Cost related to source size

Method	Measures or Defects	Applications	Advantages	Limitations
Radiog-raphy (X-rays—film)	Internal defects and variations; porosity; inclusions; cracks; lack of fusion; geometry variations; corrosion thinning Density variations Thickness, gap and position Misassembly Misalignment	Castings Electrical assemblies Weldments Small, thin, complex wrought products Nonmetallics Solid propellant rocket motors Composites	Permanent records; film Ajustable energy levels (5 kv·25 mev) High sensitivity to density changes No couplant required Geometry varia-tions do not effect direction of X-ray beam	High initial costs Orientation of linear defects in part may not be favorable Radiation hazard Depth of defect not indicated Sensitivity decreases with increase in scattered radiation
Radiometry (X-ray, gamma-ray, beta-ray) (Transmis-sion or backscat-ter)	Wall thickness Plating thickness Variations in density or composition Fill level in cans or containers Inclusions or voids	Sheet, plate, foil, strip, tubing Nuclear reactor fuel rods Cans or containers Plated parts Composites	Fully automatic Fast Extremely accurate In-line process control Portable	Radiation hazard Beta-ray useful for ultrathin coatings only Source decay Reference stan-dards required
Sonic (Less than 0.1 MHz)	Debonded areas or delaminations in metal or nonmetal composites or laminales Cohesive bond strength under con-trolled conditions Crushed or frac-tured core Bond integrity of metal insert fasteners	Metal or nonmetal composite or lam-inates brazed or adhesive-bonded Plywood Rocket motor nozzles Honeycomb	Portable Easy to operate Locates far-side debonded areas May be auto-mated Access to only one surface required	Surface geometry influences test results Reference stan-dards required Adhesive or core thickness varia-tions influence results
Thermal (thermo-chromic paint, liquid crystals)	Lack of bond Hot spots Heat transfer Isotherms Temperature ranges Blockage in coolant passages	Brazed joints Adhesive-bonded joints Metallic platings or coatings Electrical assem-blies Temperature monitoring	Very low initial cost Can be readily applied to surfaces which may be difficult to inspect by other methods No special opera-tor skills	Thin-walled surfaces only Critical time-temperature relationship Image retentivity effected by hu-midity Reference stan-dards required

Method	Measures or Defects	Applications	Advantages	Limitations
Thermo-electric probe	Thermoelectric v Coating thickness Physical properties Thompson effect P-N junctions in semiconductors	Metal sorting Ceramic coating thickness on metals Semiconductors	Portable Simple to operate Access to only one surface required	Hot probe Difficult to automate Reference standards required Surface contaminants Conductive coatings
Tomography	Boundaries Surface reconstruction Crack size, location, and orientation	Metals research Medicine	Pinpoint defect location Image display is computer controlled	Very expensive Need highly trained operator
Ultrasonic (0.1·25 MHz)	Internal defects and variations; cracks, lack of fusion, porosity, inclusions, delaminations, lack of bond,texturing Thickness or velocity Poisson's ratio, elastic modulus	Wrought metals Welds Brazed joints Adhesive-bonded joints Nonmetallics In-service parts	Most sensitive to cracks Test results know immediately Automating and permanent record capability Portable High penetration capability	Couplant required Small, thin, complex parts may be difficult to check Reference standards required Trained operator for manual inspection Special probes
Ultrasonic angle reflectivity	Elastic properties acoustic attenuation in solids Near-surface metallic property gradients, e.g. carburization in steel Metallic grain structure and size	Metals Nonmetals	Access to only one surface required Permanent record Quantitative No physical contact of sample required Sample preparation minimal	Test parts must be immersed Geometry limitations: test part must have a flat, smooth area Goniometer device required Skilled technician required

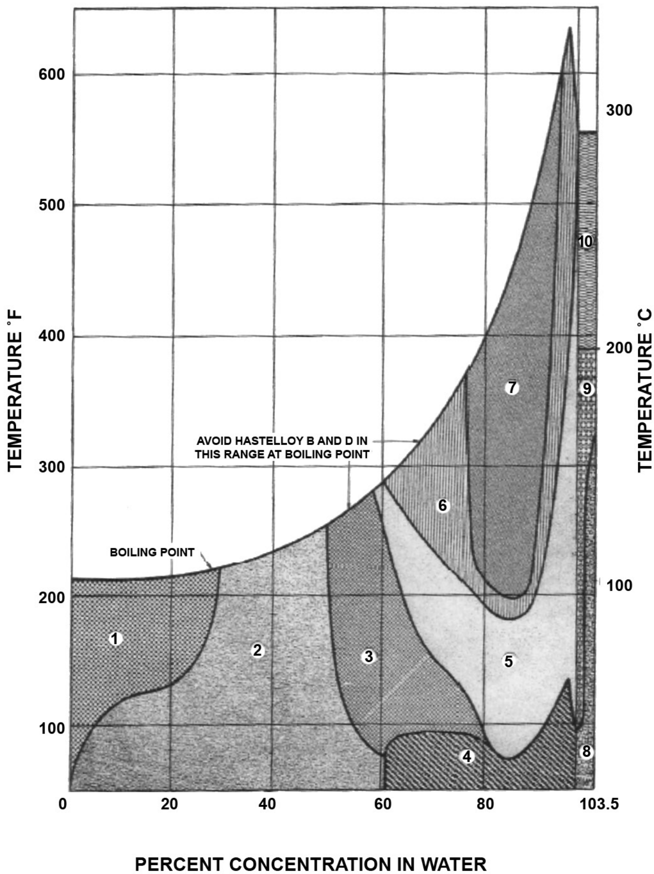
Source: *Metals Progress Databook* (Materials Park, OH, USA: ASM International, 1985), pp. 127–131 with additions. Reprinted with permission from ASM International.

CAUSTIC SODA SERVICE CHART



Source: D.L. Graver, *Corrosion Data Survey- Metals Section,* 6th ed. (Houston, TX, USA: NACE International, 1985).

SULFURIC ACID SERVICE GRAPH



Source: D.L. Graver, *Corrosion Data Survey- Metals Section,* 6th ed. (Houston, TX, USA: NACE International, 1985).

CODE FOR SULFURIC ACID GRAPH

ZONE 1
20Cr 30Ni
66NI 32Cu[3]
62Ni 28Mo
Type 316[2]
Al bronze 10%[1]
Copper[1]
Gold
Lead
Molybdenum
Nicket cast iron
Platinum
Silver
Tantalum
Zirconium

ZONE 2
20 Cr 30Ni[3]
66Ni 32Cu[1]
62Ni 28Mo
Type 316[5]
Al bronze 10%[1]
Copper[1]
Gold
Lead
Molybdenum
Nickel cast iron[4]
Platinum
Silicon cast iron
Silver
Tantalum
Zirconium

ZONE 3
20Cr 30Ni[3]
66Ni 32Cu[1]
62Ni 28Mo
Gold
Lead
Molybdenum
Platinum
Silicon iron
Tantalum
Zirconium

ZONE 4
20Cr 30Ni
62Ni 28Mo
Type 316[7]
Gold
Lead[6]
Nickel cast iron
Platinum
Silicon iron
Steel
Tantalum
Zirconium[8]

ZONE 5
20Cr 30Ni[3]
62Ni 28Mo
Gold
Lead[9]
Platinum
Silicon iron
Tantalum

ZONE 6
62Ni 28Mo[10]
Gold
Platinum
Silicon iron
Tantalum

ZONE 7
Gold
Platinum
Silicon iron
Tantalum

ZONE 8
20Cr 30Ni
18Cr 8Ni
54Ni 15Cr 16Mo
Gold
Platinum
Steel

ZONE 9
20Cr 30Ni
18Cr 8Ni
Gold
Platinum

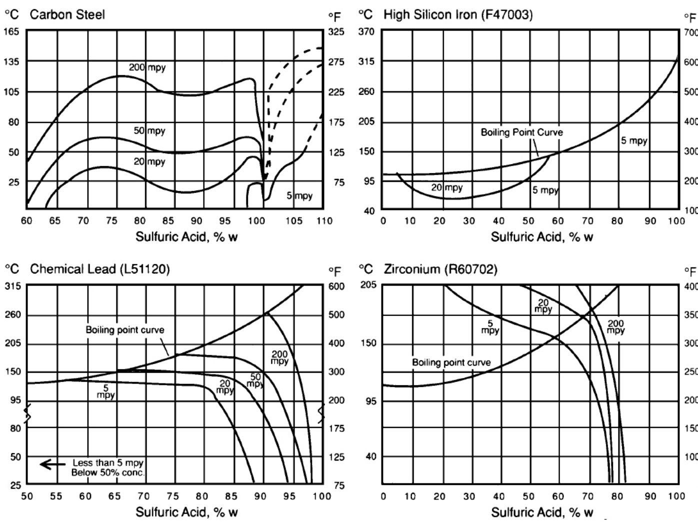
ZONE 10
Gold
Platinum

1. No air
2. < 10% aerated
3. <75 ˚C
4. < 20% at 25 ˚C
5. < 25% aerated at 25 ˚C
6. <96% concentration
7. >80% concentration
8. <80% aerated
9. <75 ˚C, <96%
10. 20 to 50 mpy

Source: D.L. Graver, *Corrosion Data Survey- Metals Section,* 6th ed. (Houston, TX, USA: NACE International, 1985).

ALLOYS FOR SULFURIC ACID SERVICE

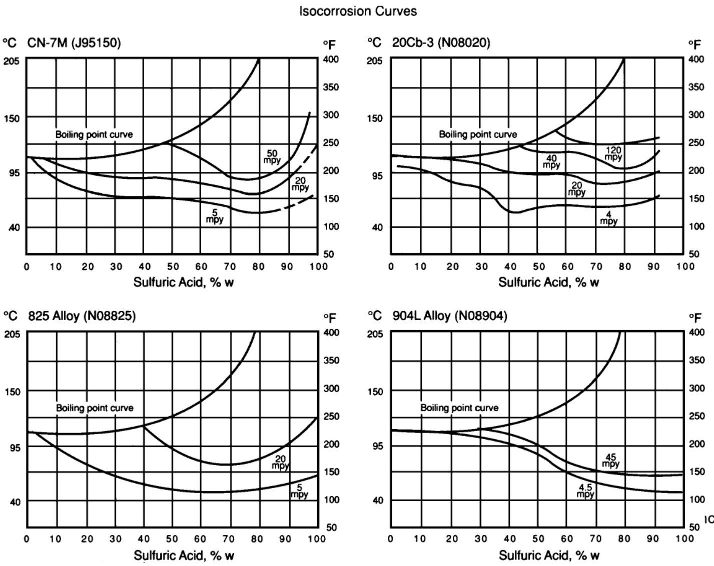
Isocorrosion Curves



Note: These graphs are based on laboratory tests with pure acid, and should be used for general guidance only. For detailed information see *Process Industries Corrosion—The Theory and Practice* (NACE International, 1986).

Sources: M.G. Fontana, *Corrosion Engineering* (New York, NY, USA: McGraw-Hill, 1986) and R.T. Webster, T.L. Yau, "Zirconium in Sulfuric Acid Applications" *MP* 25, 2 (1986): p. 15.

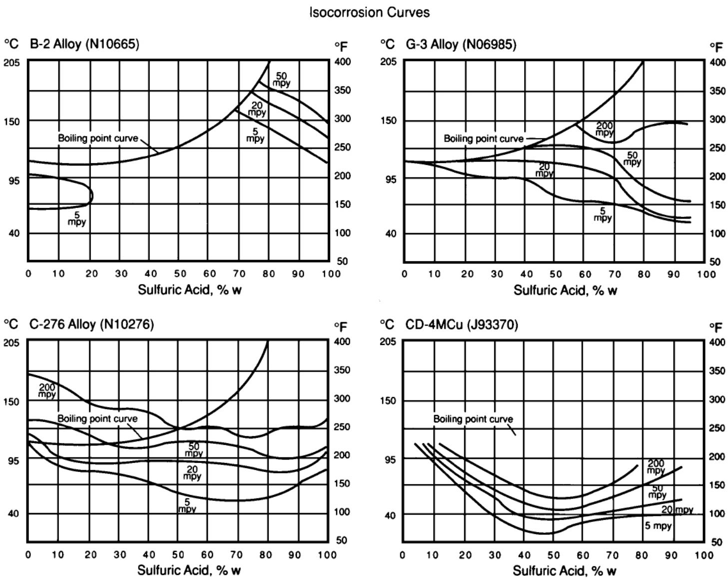
ALLOYS FOR SULFURIC ACID SERVICE



Note: These graphs are based on laboratory tests with pure acid, and should be used for general guidance only. For detailed information see *Process Industries Corrosion—The Theory and Practice* (NACE International, 1986).

Source: Corrosion Engineering Bulletin 1, The International Nickel Company, 1983.

ALLOYS FOR SULFURIC ACID SERVICE

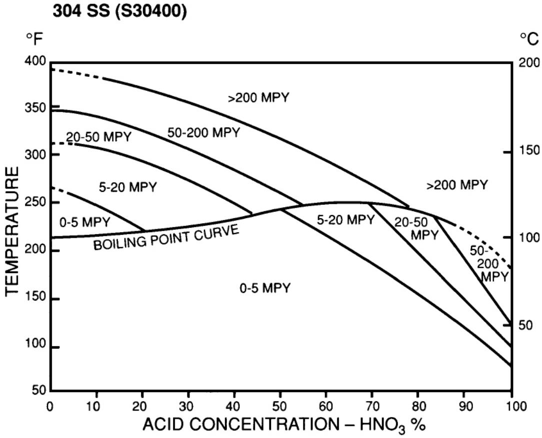


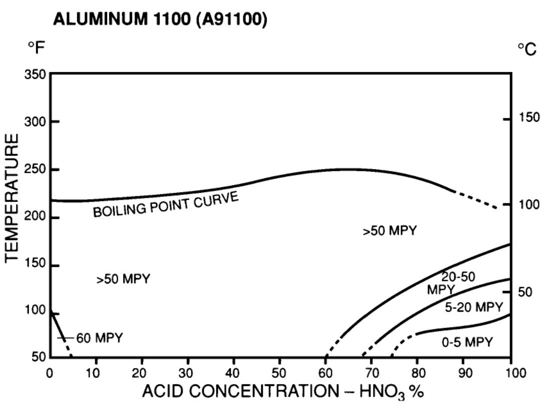
Note: These graphs are based on laboratory tests with pure acid, and should be used for general guidance only. For detailed information see *Process Industries Corrosion—The Theory and Practice* (NACE International, 1986).

Sources: Corrosion Engineering Bulletin 1, The International Nickel Company, 1983 and Hastelloy Alloy G-3 Booklet, Cabot Corporation, 1983.

ALLOYS FOR NITRIC ACID SERVICE

Isocorrosion Curves

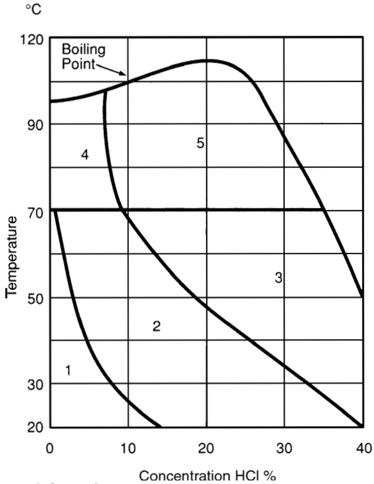




Note: These graphs are based on laboratory tests with pure acid, and should be used for general guidance only. For detailed information see *Process Industries Corrosion—The Theory and Practice* (NACE International, 1986).

Source: M.G. Fontana, *Corrosion Engineering* (New York, NY, USA: McGraw-Hill, 1986).

ALLOYS FOR HYDROCHLORIC ACID SERVICE



Materials in numbered zones have reported corrosion rates of <20 mpy

Zone 1

CN-7M	(1) (3) (6)
400 Alloy	(2) (3) (6)
Copper	(2) (3) (6)
Nickel 200	(2) (3) (6)
Silicon Bronze	(2) (3) (6)
Silicon Cast Iron	(7)
Tungsten	
Titanium (Gr. 7)	
Titanium (Gr. 2)	(4)

Zone 2

Silicon Bronze	(2) (6)
Silicon Cast Iron	(7)

Zone 3

Silicon Cast Iron	(7)

Zone 4

400 Alloy	(2) (3) (8)
Tungsten	
Titanium (Gr.7)	(5)

All Zones (including 5)

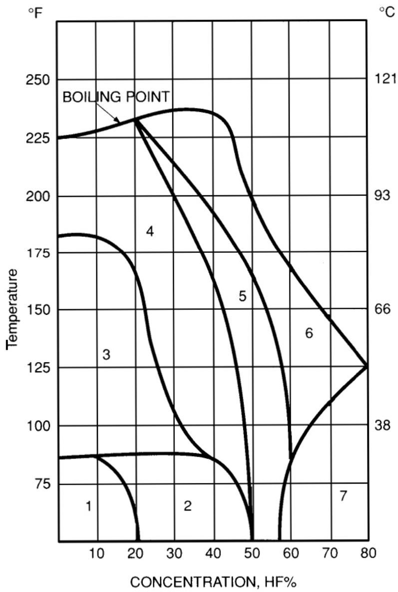
Platinum	
Tantalum	
Silver	(3) (6)
Zirconium	(3) (6)
B-2 Alloy	(3) (6)
Molybdenum	(3) (6)

Notes:
1. <2% at 25 °C
2. No Air
3. No $FeCl_3$ or $CuCl_2$
4. <10% at 25 °C
5. <5% at B.P.
6. No Chlorine
7. Cr-Mo Alloy
8. <0.05% Concentration

Note: These graph should be used for general guidance only. For more detailed information see *Process Industries Corrosion—The Theory and Practice* (NACE International, 1986).

Source: D.L. Graver, *Corrosion Data Survey- Metals Section*, 6th ed. (Houston, TX, USA: NACE International, 1985). Modified by T.F. Degnan.

ALLOYS FOR HYDROFLUORIC ACID SERVICE



Materials in numbered zones have reported corrosion rates of <20 mpy

Zone 1

CN-7M
310 SS
70-30 Cu-Ni*
400 Alloy*
C Alloy
Copper*
Gold
Lead*
Nickel*
Nickel cast iron
Platinum
Silver

Zone 2

CN-7M
70-30 Cu-Ni*
400 Alloy*
C Alloy
Copper*
Gold
Lead*
Nickel*
Platinum
Silver

Zone 3

CN-7M
70-30 Cu-Ni*
400 Alloy*
C Alloy
Copper*
Gold
Lead*
Platinum
Silver

Zone 4

70-30 Cu-Ni*
400 Alloy*
C Alloy
Copper*
Gold
Lead*
Platinum
Silver

Zone 5

70-30 Cu-Ni*
400 Alloy*
C Alloy
Gold
Lead*
Platinum
Silver

Zone 6

400 Alloy*
C Alloy
Gold
Platinum
Silver

Zone 7

400 Alloy*
C Alloy
Carbon Steel
Gold
Platinum
Silver

*No Air

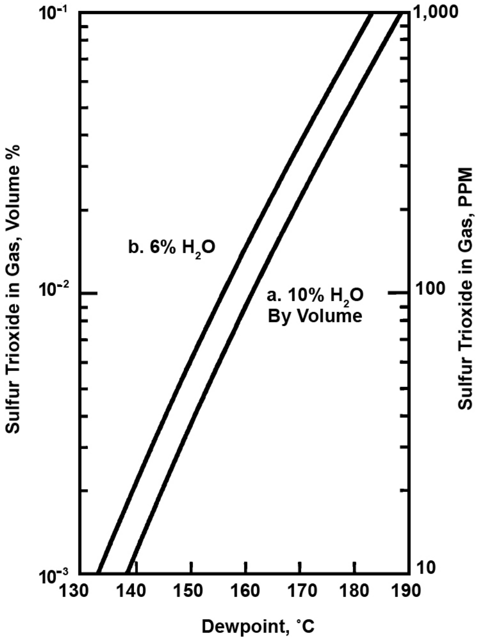
Note: These graph should be used for general guidance only. For more detailed information see *Process Industries Corrosion—The Theory and Practice* (NACE International, 1986).

Source: D.L. Graver, *Corrosion Data Survey- Metals Section*, 6th ed. (Houston, TX, USA: NACE International, 1985).

ESTIMATE OF SULFUR TRIOXIDE IN COMBUSTION GAS

Sulfur in Fual (%)		0.5	1.0	2.0	3.0	4.0	5.0
Excess Air (%)	Oxygen in Gas (%)	Sulfur Trioxide Expected in Gas (ppm) Oil Fired Units					
5	1	2	3	3	4	5	6
11	2	6	7	8	10	12	14
17	3	10	13	15	19	22	25
25	4	12	15	18	22	26	30
Coal Fired Units							
25	4	3–7	7–14	14–28	20–40	27–54	33–66

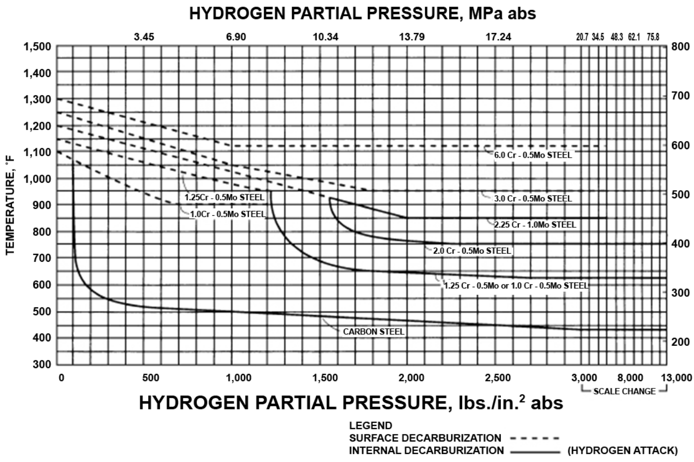
CALCULATED SULFURIC ACID DEWPOINT IN FLUE GAS



Calculated dewpoint vs sulfur trioxide concentration: (a) 10% H_2O from oil; and (b) 6% H_2O from coal.

Source: R.D. Tems, T.E. Mappes, "Corrosion of Particulate Control Equipment," *MP* 21, 12 (1982): p. 26.

OPERATING LIMITS FOR STEELS IN HYDROGEN SERVICE TO AVOID DECARBURIZATION AND FISSURING



See current edition of API Publication 941 for detailed comments, including special comments regarding 0.5Mo Steel.

Source: Adapted from API Publication 941 "Steels for Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Petrochemical Plants" (Washington DC, USA: American Petroleum Institute, 1990).

LIQUID METAL CRACKING

Couples identified below are those combinations of solid metal and liquid metal that have resulted in embrittlement in tests with either the pure element or an alloy. This compilation is a summary of data from the indicated source.

Solid	Liquid
Aluminum	Hg Ga Na In Sn Bi Cd Pb Zn
Bismuth	Hg
Cadmium	Cs Ga Sn
Copper	Hg Ga Na In Li Sn Bi Pb
Germanium	Ga In Sn Bi Tl Cd Pb Sb
Iron	Hg Ga In Li Sn Cd Pb Zn Te Sb Cu
Magnesium	Na Zn
Nickel	Hg Li Sn Pb
Palladium	Li
Silver	Hg Ga Li
Tin	Hg Ga
Titanium	Hg Cd
Zinc	Hg Ga In Sn Pb

Source: L.J. Korb, *Metals Handbook,* 9th ed., vol. 13 (Materials Park, OH, USA: ASM International, 1987), p. 182. Reprinted with permission from ASM International.

STRESS CORROSION CRACKING SYSTEMS

Below is a partial listing of alloy/environment systems where stress corrosion cracking (anodic type) may occur. Whether cracking occurs in a specific system depends on temperature, environment composition, tensile stress level, alloy composition, and heat treatment.

Alloy	Environment
Aluminum alloys	Chloride solutions
Magnesium alloys	Chloride solutions
Copper alloys	Ammonia + oxygen + water Amines + oxygen + water Nitric acid vapor Steam
Carbon and low alloy steels	Nitrate solutions Caustic solutions Carbonate solutions Alkanolamines + carbon dioxide Carbon monoxide – carbon dioxide + water Anhydrous ammonia + air Hydrogen cyanide solutions
Austenitic stainless steels and some ferritic and duplex stainless steels	Chloride and bromide solutions Organic chlorides and bromides + water Caustic solutions H_2S solutions – chlorides or oxidants
Nickel alloys	Caustic solutions Fused caustic Hydrofluoric acid H_2S solutions – chlorides or oxidants
Titanium alloys	Aqueous salt systems Methanol plus halides Nitrogen tetroxide
Zirconium alloys	Aqueous salt systems Nitric acid
Sensitized austenitic stainless steels	Water – oxygen (high temperature) Chloride solutions Polythionic acid solutions Sulfurous acid

HYDROGEN STRESS CRACKING may occur with high strength alloys (carbon and low alloy steels, some stainless steels, and some nickel-base alloys) in a number of environments including:
Hydrogen sulfide solutions (SULFIDE STRESS CRACKING, SSC)

See following page for information on hydrogen degradation systems, and for H_2S concentration limit for SSC.

CLASSIFICATIONS OF PROCESSES OF HYDROGEN DEGRADATION OF METALS

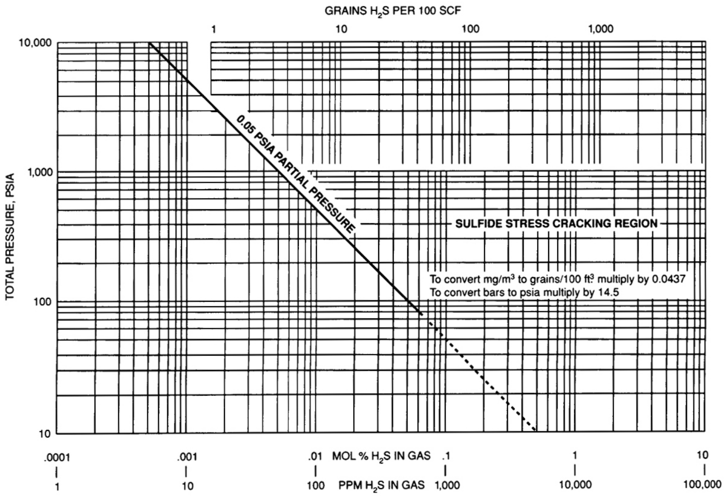
	Hydrogen Embrittlement								
	Hydrogen Environment Embrittle-ment	**Hydrogen Stress Cracking**	**Loss in Tensile Ductility**	**Hydrogen Attack**	**Blistering**	**Shatter Cracks, Flakes, Fisheyes**	**Micro-Perfora-tion**	**Degradation in Flow Prop-erties**	**Metal Hydride Formation**
Typical materials...	Steels, nickel-base alloys, metastable stainless steel, titanium alloys	Carbon and low-alloy steels	Steels nickel-base alloys. Be-Cu bronze, aluminum alloys	Carbon and low-alloy steels	Steels, copper, aluminum	Steels (forgings and castings)	Steels (com-pressors)	Iron, steels, nickel-base alloys	V, Nb, Ta, Ti, Zr, U,
Usual source of hydrogen (not exclusive)...	Gaseous H_2	Thermal processing, electrolysis, corrosion	Gaseous hydrogen, internal hydrogen from elec-trochemical charging	Gaseous	Hydrogen sulfide corrosion electrolytic charging, gaseous	Water vapor reacting with molten steel	Gaseous hydrogen	Gaseous or internal hydrogen	Internal hydrogen from melt: corrosion, electrolytic charging, welding

	Hydrogen Environment Embrittlement	Hydrogen Stress Cracking	Loss in Tensile Ductility	Hydrogen Attack	Blistering	Shatter Cracks, Flakes, Fisheyes	Micro-Perforation	Degradation in Flow Properties	Metal Hydride Formation
Typical conditions...	10^{-6} to 10^{8} N/m² (10^{-10} to 10^{4} psi) gas pressure	0.1 to 10 ppm total hydrogen content	0.1 to 10 ppm total hydrogen content range of gas pressure exposure	Up to 10^{8} N/m² (15 ksi) at 200–595 °C (400–1,100 °F)	Hydrogen activity equivalent to 0.2 to 1 × 10^{8} N/m² (3–15 ksi) at 0–150 °C (30–300 °F)	Precipitation of dissolved ingot cooling	2 to 8 × 10^{8} N/m² (30–125 ksi) at 20–100 °C (70–200)	1–10 ppm hydrogen content (iron at 20 °C, or 70 °F) up to 10^{8} N/m² (15 ksi) gaseous hydrogen (various metals, *T* > 0.5 melting point)	10^{5} to 10^{8} N/m² (15–15,000 psi) gas pressure hydrogen activity must exceed solubility limit near 20 °C (70 °F) Failure
	Observed at −100 to 700 °C (−150 to 1,290 °F); most severe near 20 °C (70 °F)	Observed at −100 to 100 °C (−150 to 212 °F); most severe near °C (70 °F)	Observed at −100 to 700 °C (−150 to 1,290 °F)	...	...	...	...	...	...
	Strain rate important; embrittlement more severe at low strain rate; generally more severe precracked specimens	Strain rate important; embrittlement more severe at low strain rate; always more severe in notched or precracked	Occurs in absence of effect on yield stress; strain rate important in notched or specimens	...	...	...	...	...	...

	Hydrogen Environment Embrittlement	Hydrogen Stress Cracking	Loss in Tensile Ductility	Hydrogen Attack	Blistering	Shatter Cracks, Flakes, Fisheyes	Micro-Perforation	Degradation in Flow Properties	Metal Hydride Formation
Failure initiation.......	Surface or internal initiation, incubation period not observed	Internal crack initiation ...	Surface and/or internal effect	Surface (decarburization); internal carbide interfaces (methane bubble formation)	Internal defect	Internal defect	Unknown	...	Internal defect
Mechanisms......	Surface or subsurface processes	Internal diffusion to stress concentration	Surface or subsurface processes	Carbon diffusion (decarburization); hydrogen diffusion; nucleation and growth (bubble formation)	Hydrogen diffusion; nucleation and growth of bubble; steam formation	Hydrogen diffusion to voids	Unknown	Adsorption to dislocations; solid-solutions effects	Hydride precipitation

Source: J.P. Hirth, H.H. Johnson, "Hydrogen Problems in Energy Related Technology," *Corrosion* 32, 1 (1976): p. 3.

POTENTIAL SULFIDE STRESS CRACKING REGION AS DEFINED BY THE 0.05 PSIA CRITERION



Source: NACE Publication MRO175-2000 "Standard Material Requirements- Sulfide Stress Cracking Resistant Metallic Materials for Oilfield Equipment" (Houston, TX, USA: NACE International, 2000).

COMPOSITIONS OF SELECTED WROUGHT IRON-NICKEL-CHROMIUM AND NICKLE-BASE ALLOYS FOR HIGH-TEMPERATURE CHEMICAL PROCESSING ENVIRONMENTS

Alloy	UNS No.	Ni	Fe	Cr	Al	Others
253MA	S30815	11	bal	21	...	1.6Si, 0.05 Ce
800H/HT	N08800	32	bal	21	0.4	0.4Ti
330	N08330	35	bal	19	...	1.3Si
353MA	S35315	35	bal	25	...	1.6Si, 0.05Ce, 0.15N
803	S35045	35	bal	27	0.3	0.4Ti
HR-120	N08120	37	bal	25	...	0.7Nb, 0.2N
556	R30556	20	bal	22	...	18Co, 0.6Ta, 0.2N
45TM	N06045	bal	23	27	...	2.7Si, 0.06Ce
HR-160	N12160	bal	3.5(a)	28	...	29Co, 2.75Si, 0.5Ti, 0,5Nb
601	N06601	bal	14	23	1.4	...
602CA	N06025	bal	9	25	2.1	0.08Y, 0.05Zr
X	N06602	bal	18	22	...	9Mo, 0.6W
333	N06333	bal	18	25	...	3Mo, 3W
617	N06617	bal	1.5	22	1.2	12.5Co, 9Mo
230	N06230	bal	3(a)	22	...	14W, 5Co max, 2 Mo, 0.02La
214	N07214	bal	3	16	4.5	0.01Y, 0.05Zr max
MA 956(b)	S67956	...	bal	20	4.5	0.5Y_2O_3

Source: S.D. Cramer, B.S. Covino, Jr., *ASM Handbook Volume 13C: Corrosion: Environments and Industries* (Materials Park, OH, USA: ASM International, 2006), p. 755.

MAXIMUM TEMPERATURE FOR CONTINUOUS SERVICE IN DRY HYDROGEN CHLORIDE AND DRY CHLORINE

Material	Hydrogen Chloride		Chlorine	
	˚C	˚F	˚C	˚F
Platinum	1,200	2,200	260	500
Gold	870	1,600	150	300
Nickel	510	950	540	1,000
Ni-Cr alloy 600	480	900	540	1,000
Ni-Mo alloy B	450	850	540	1,000
Ni-Mo-Cr alloy C	450	850	540	950
Carbon steel	260	500	200	400
Ni-Cu alloy 400	230	450	430	800
Silver	230	450	65	150
Cast iron	200	400	180	350
304SS	400	750	310	600
316SS	400	750	340	650
Copper	93	200	200	400

Source: M.H. Brown, W.B. DeLong, J.R. Auld, "Corrosion by Chlorine and by Hydrogen Chloride at High Temperatures," *Industrial Engineering & Chemistry* 39, 7 (1947): p. 839. Copyright American Chemical Society.

APPROXIMATE TEMPERATURES AT WHICH THE INDICATED CORROSION RATE OCCURS IN DRY CHLORINE

	Temperature for corrosoin rate, mm/yr. (mils/yr.)											
	0.76 (30)		1.5 (60)		3 (120)		15 (600)		30 (1,200)		Maximum [a]	
Alloy	˚C	˚F	˚C	˚F	˚C	˚F	˚C	˚F	˚C	˚F	˚C	˚F
Nickel 201	510	950	540	1,000	590	1,100	650	1,200	680	1,250	540	1,000
Inconel 600	510	950	540	1,000	565	1,050	650	1,200	680	1,250	540	1,000
Hastelloy B	510	950	540	1,000	590	1,100	650	1,200	...	...	540	1,000
Hastelloy C	480	900	540	1,000	560	1,050	650	1,200	...	...	510	950
Magnesium	450	850	480	900	510	950	540	1,000	565	1,050	450	850
Ni-20Cr-1Si	425	800	480	900	540	1,000	620	1,150	...	...	450	850
Monel 400	400	750	450	850	480	900	540	1,000	540	1,000	420	800
Type 316 stainless steel	310	600	345	650	400	750	450	850	480	900	340	650
Type 304 stainless steel	290	550	315	600	340	650	400	750	450	850	310	600
Platinum	480	900	510	950	540	1,000	560	1,050	560	1,050	260	500
Hastelloy D	205	400	230	450	290	550	...	...	...	...	205	400
Deoxidized copper	180	350	230	450	260	500	260	500	290	550	205	400
Carbon steel	120	250	180	350	205	400	230	450	230	450	205	400
Cast iron	90	200	120	250	180	350	230	450	230	450	180	350
Aluminum alloy 1100	120	250	150	300	150	300	180	350	180	350	120	250
Gold	120	250	150	300	180	350	200	400	200	400	...	...
Silver	40	100	65	150	120	250	230	450	260	500	...	...

[a] Suggest upper temperature limit for continuous service

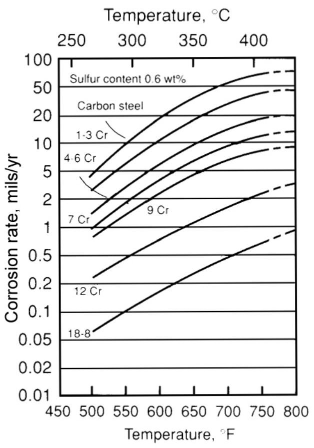
Source: S.D. Cramer, B.S. Covino, Jr., *ASM Handbook Volume 13C: Corrosion: Environments and Industries* (Materials Park, OH, USA: ASM International, 2006), p. 705.

MAXIMUM SERVICE TEMPERATURES IN AIR FOR STAINLESS STEELS AND ALLOY STEELS

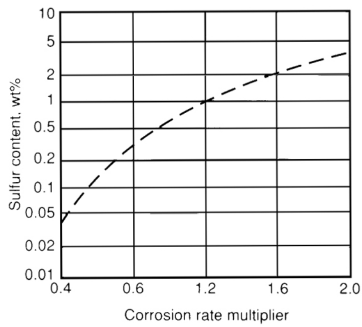
UNS	Common Name	Maximum ServiceTemperature			
		Intermittent Service		Continuous Service	
		˚C	˚F	˚C	˚F
S20100	201	815	1,500	845	1,550
S20200	202	815	1,500	845	1,550
S30100	301	840	1,545	900	1,650
S30200	302	870	1,600	925	1,700
S30400	304	870	1,600	925	1,700
S30800	308	925	1,700	980	1,795
S30900	309	980	1,795	1,095	2,000
S31000	310	1,035	1,895	1,150	2,100
S31600	316	870	1,600	925	1,700
S31700	317	870	1,600	925	1,700
S32100	321	870	1,600	925	1,700
S33000	330	1,035	1,895	1,150	2,100
S34700	347	870	1,600	925	1,700
S40500	405	815	1,500	705	1,300
S43000	430	870	1,600	815	1,500
S44200	442	1,035	1,895	980	1,795
S44600	446	1,175	2,145	1,095	2,000
S41000	410	815	1,500	705	1,300
S41600	416	760	1,400	675	1,250
S42000	420	735	1,355	620	1,150
S44000	440	815	1,500	760	1,400
	Carbon Steel	-	-	565	1,050
K11522	1/2Mo Steel	-	-	565	1,050
K11597	1Cr 1/2Mo Steel	-	-	595	1,100
K21590	2-1/4Cr 1Mo Steel	-	-	620	1,150
K41545	5Cr 1/2Mo Steel	-	-	650	1,200
S50400	9Cr 1Mo Steel	-	-	705	1,300

Source: L.J. Korb, *Metals Handbook,* 9th ed., vol. 13 (Materials Park, OH, USA: ASM International, 1987), p. 20. Reprinted with permission from ASM International.

HIGH-TEMPERATURE SULFIDIC CORROSION OF STEELS AND STAINLESS STEELS



Modified McConomy curves showing the effect of temperature on high-temperature sulfidic corrosion of various steels and stainless steels.



Effect of sulfur content on corrosion rates predicted by modified McConomy curves in 290 to 400 °C (550 to 750 °F) temperature range.

Source: J. Gutzeit, *Process Industries Corrosion–The Theory and the Practice* (Houston, TX, USA: NACE International, 1986).

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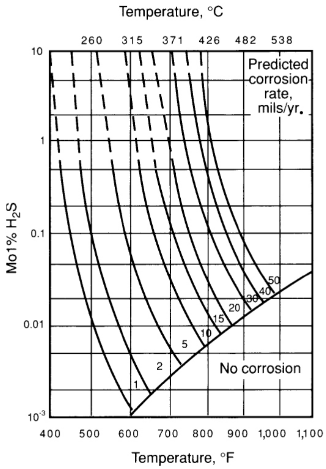
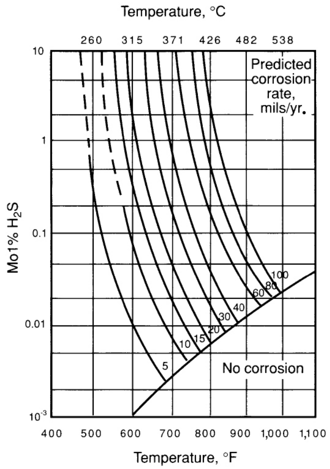
HIGH-TEMPERATURE H_2S/H_2 CORROSION OF 5Cr-0.5Mo STEEL



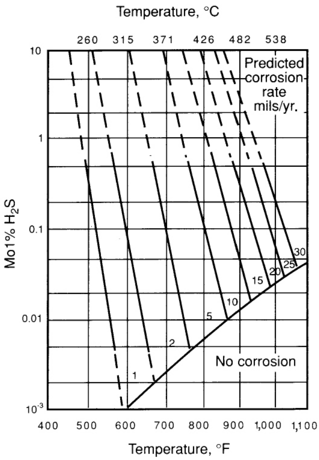
Effect of temperature and hydrogen sulfide content on high temperature H_2S/H_2 corrosion of 5Cr-0.5Mo steel (naphtha desulfurizers). 1 mil/yr. = 0.025 mm/yr.



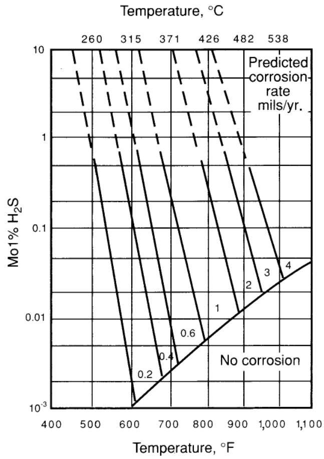
Effect of temperature and hydrogen sulfide content on high- temperature H_2S/H_2 corrosion of 5Cr-0.5Mo steel (gas oil desulfurizers). 1 mil/yr. = 0.025 mm/yr.

Source: J. Gutzeit, *Process Industries Corrosion–The Theory and the Practice* (Houston, TX, USA: NACE International, 1986).

HIGH-TEMPERATURE H_2S/H_2 CORROSION OF STAINLESS STEELS



Effect of temperature and hydrogen sulfide conter on high-temperature H_2S/H_2 corrosion of 12% Cr stainless steel. 1 mil/yr. = 0.025 mm/yr.



Effect of temperature and hydrogen sulfide content on high-temperature H_2S/H_2 corrosion of 18Cr-8Ni austenitic stainless steel. 1 mil/yr. = 0.025 mm/yr.

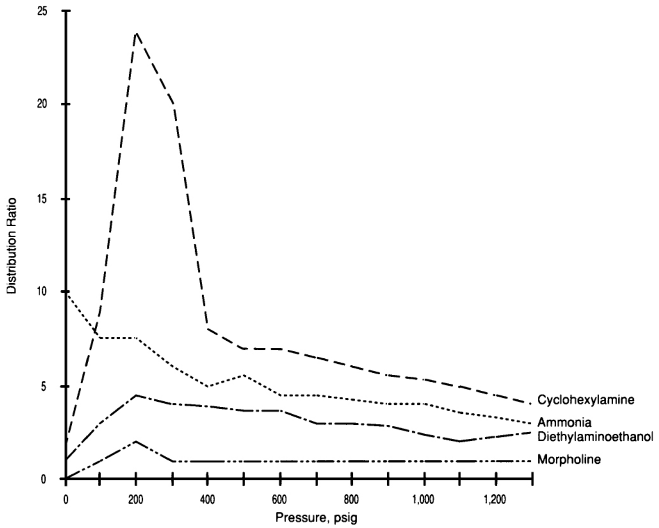
Source: J. Gutzeit, *Process Industries Corrosion–The Theory and the Practice* (Houston, TX, USA: NACE International, 1986).

ASH FUSION TEMPERATURE OF SLAG-FORMING COMPOUNDS

Chemical Compound	Chemical Formula	Ash Fusion Temperature °C	°F
Vanadium pentoxide	V_2O_5	690	1,274
Sodium sulfate	Na_2SO_4	890	1,630
Nickel sulfate	$NiSO_4$	840	1,545
Sodium metavanadate	$Na_2O \cdot V_2O_5$	630	1,165
Sodium pyrovanadate	$2Na_2O \cdot V_2O_5$	655	1,210
Sodium orthovanadate	$3Na_2O \cdot V_2O_5$	865	1,590
Nickel orthovanadate	$3NiO \cdot V_2O_5$	900	1,650
Sodium vanadyl vanadate	$Na_2O \cdot V_2O_4 \cdot 5V_2O_5$	625	1,155
Sodium iron trisulfate	$2Na_3Fe[SO_4]_3$	620	1,150

Source: L.J. Korb, *Metals Handbook*, 9th ed., vol. 13 (Materials Park, OH, USA: ASM International, 1987), p. 1,273. Reprinted with permission from ASM International.

DISTRIBUTION RATIO OF AMMONIA AND AMINES IN STEAM AND STEAM CONDENSATE



Concentration of amine in steam Distribution Ratio = Concentration of amine in steam/Concentration of amine in liquid

Source: *Oil and Gas Journal* (Nov. 9, 1987): p. 66. Reprinted with permission from Oil and Gas Journal.

COMMON TYPES OF SCALE-FORMING MINERALS

Scale	X-ray Analysis
Acmite - Sodium Iron Silicate	$NaFe(SiO_3)_2$
Barite - Barium Sulfate	$BaSO_4$
Anaicite - Sodium Aluminum Silicate	$NaAl\ Si_2O_5 \cdot H_2O$
Aragonite - (Rhombic Crystals)	$CaCO_3$
Calcium Carbonate - (Hexagonal Crystal)	$CaCO_3$
Calcium Sulfate - Anhydrite	$CaSO_4$
Hydromagnesite - Magnesium Carbonate and Hydroxide	$3MgCO_3 \cdot Mg(OH)_2 \cdot 3H_2O$
Hydroxyapatite - Calcium Phosphate	$Ca_{10}(OH)_2(PO_4)_6$
Iron Oxide	Alpha FeO (OH)
Iron Oxide - Magnetite	Fe_3O_4
Iron Oxide - Red	Fe_2O_3
Iron Chrome Spinels	$CrFe_2O_4$
Iron Sulfide - Troilite, Pyrrhotite	FeS
Magnesium Hydroxide - Bricite	$Mg(OH)_2$
Magnesium Oxide - Magnesia	MgO
Manganese Dioxide - Pyrolusite	MnO_2
Montmorillonite - Aluminum Silicate	$Al_2O_3 \cdot 4SiO_2 \cdot 4H_2O$
Noselite - Sodium Aluminum Silicate	$Na_8Al_6Si_6O_{24} \cdot SO_4$
Organic Deposits	
Pectolite - Calcium Sodium Silicate	$4CaO \cdot Na_2O \cdot 6SiO_2 \cdot H_2O$
Serpentine - Magnesium Silicate	$Mg_3Si_2O_7 \cdot 2H_2O$
Silica - Quartz	SiO_2
Sodalite - Sodium Aluminum Silicate	$Na_8Al_6Si_6O_{24} \cdot Cl_2$
Vermiculite - Magnesium Iron Aluminum Silicate	$(Mg \cdot Fe)_3(Si \cdot Al)_4O_{10}(OH)_2 \cdot 4H_2O$
Xonolite - Calcium Silicate	$5CaO \cdot 5SiO_2 \cdot H_2O$

The compounds listed below are usually found in industrial equipment which contains copper, brass, or bronze:

Copper Iron Sulfide	CuFeS
Copper Sulfide - Covellite, Chalcocite	CuS and Cu_2S
Basic Copper Chloride	$CuCl_2 \cdot 3Cu(OH)_2$
Copper Oxide - Cuprite	Cu_2O
Chalcopyrite	$CuFeS_2$
Beta Zinc Sulfide - Sphalerite	ZnS
Green Basic Carbonate - Malachite	$CuCO_3\ Cu(OH)_2$

Source: NACE Publication 3M182 (withdrawn). "Corrosion Testing of Chemical Cleaning Solvents." (Houston, TX, USA: NACE International, 1982).

CHEMICAL CLEANING SOLUTIONS FOR SPECIFIC SCALES

Scale Component	Solvent*	Testing Conditions
Iron Oxide	5 to 15% HCl	66–80 ˚C (150–175 ˚F)
Fe_3O_4 magnetite or mill scale	2% Hydroxyacetic/ 1 Formic	82–104 ˚C (180–220 ˚F) circulating
	Monoammoniated Citric Acid	82–104 ˚C (180–220 ˚F) circulating
Fe_2O_3 red iron oxide or red rust	Ammonium EDTA	77–149 ˚C (170–300 ˚F) circulating
	EDTA organic acid mixtures	38–66 ˚C(100–150 ˚F) circulating
Copper	Copper complexor in HCl	66 ˚C (150 ˚F)
Copper Oxides	Ammoniacal Bromate	50–82 ˚C (120–180 ˚F)
	Monoammonlated Citric Acid	60–82 ˚C(140–180 ˚F), pH 9 to 11
	Ammonium Persulfate	below 38 ˚C (100 ˚F)
	Ammonium EDTA	66–82 ˚C (150–180 ˚F), pH 9 to 11
Calcium Carbonate $CaCO_3$	5 to 15% HCl	Preferable not above 66 ˚C (150 ˚F)
	7 to 10% Sulfamic Acid	Do not exceed 60 ˚C (140 ˚F)
	Sodium EDTA	Circulate at 66–149 ˚C (150–300 ˚F)
Calcium Sulfate $CaSO_4$	Sodium EDTA	Circulate at 66–149 ˚C (150–300 ˚F)
	1% NaOH · 5% HCl	Circulate at 49–66 ˚C (120–150 ˚F)
	EDTA organic acid mixtures	38–66 ˚C (100–150 ˚F) circulating
Hydroxyapatite or Phosphate Compounds	5 to 10% HCl	Preferable not above 150 ˚F (65 ˚C)
$Ca_{10}(OH)_2(PO_4)_6$	Sodium EDTA	Undesirable to add Flouride Circulate 66–149 ˚C (150–300 ˚F)
	Sulfamic Acid 7 to 10%	Do not exceed 60 ˚C (140 ˚F)

Scale Component	Solvent*	Testing Conditions
Silicate Compounds Ex: Acmite, $NaFe(SiO_3)_2$ Analcite, $NaAlSi_2O_5 \cdot H_2O$	Prolonged treatment with 0·5 to 1% soda ash at 50 psi (345 kPa), follow with HCl containing fluoride	Alkaline preboil at 345 to 690 kPa (50 to 100 psi) for 12 to 16 hours
Pectolite, $4Ca \cdot Na_2O \cdot 6SiO_2 \cdot H_2O$ Serpentine, $Mg_3Si2O_2 \cdot 2H_2O$	HCl containing Ammonium Bifluoride	66–80 °C (150–175 °F)
Sulfides, ferrousTrolite, FeS Pyrrhotite, FeS	HCl, inhibited	Heat slowly to avoid sudden release of toxic H_2S gas
Disulfides FeS_2, marcasite FeS_2 pyrite	Chromic Acid, CrO_3 followed by HCl	Boiling 7 to 10% ° chromic acid followed by HCl inhibited
Organic residues Organo · lignins Algae Some polymeric residues	Potassium Permanganate ($KMnO_4$) followed by HCl containing Oxalic Acid	Circulate at 100 °C (212 °F) a 1 to 2% $KMnO_4$ · solution. Oxalic acid added to HCl controls release of toxic chlorine gas

*The chemicals are to be considered possible solvents only. There are many alternative solvents for each deposit listed.

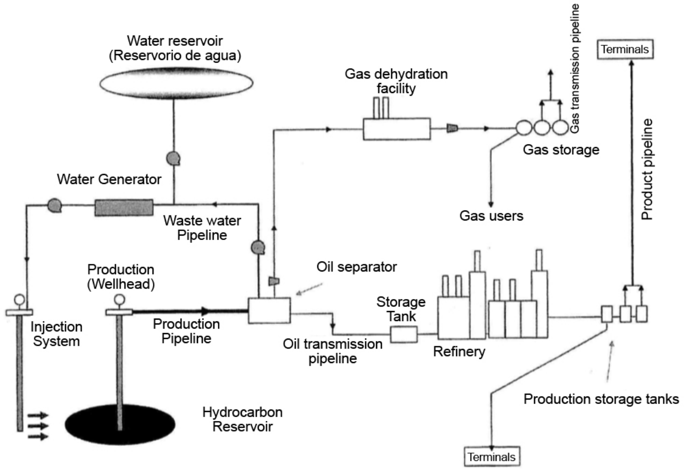
Source: NACE Publication 3M182 (withdrawn). "Corrosion Testing of Chemical Cleaning Solvents." (Houston, TX, USA: NACE International, 1982).

COMPONENTS OF BOILER DEPOSITS

Mineral	Formula	Nature of Deposit	Usual Location and Form
Acmite	$Na_2O{\cdot}Fe_2O_3{\cdot}4SiO_2$	Hard, adherent	Tube scale under hydroxyapatite or serpentine
Alpha quartz	SiO_2	Hard, adherent	Turbine blades, mud drum, tube scale
Amphibole	$MgO{\cdot}SiO_2$	Adherent binder	Tube scale and sludge
Analcite	$Na_2O{\cdot}Al_2O_3{\cdot}4SiO_2{\cdot}2H_2O$	Hard, adherent	Tube scale under hydroxyabatite or serpentine
Anhydrite	$CaSO_4$	Hard, adherent	Tube scale, generating tubes
Aragonite	$CaCO_3$	Hard, adherent	Tube scale, feed lines, sludge
Brucite	$Mg(OH)_2$	Flocculent	Sludge in mud drum and water wall headers
Copper	Cu	Electroplated layer	Boiler tubes and turbine blades
Cuprite	Cu_2O	Adherent layer	Turbine blades, boiler deposits
Gypsum Hematite	$CaSO_4{\cdot}2H_2O$ Fe_2O_3	Hard, adherent Binder	Tube scale, generating tubes Throughout boiler
Hydroxyapatite	$Ca_{10}(PO_4)_5(OH)_2$	Flocculent	Mud drum, water walls, sludge
Magnesium phosphate	$Mg_3(PO_4)_2$	Adherent binder	Tubes, mud drum, water walls
Magnetites	Fe_2O_4	Protective film	All internal surfaces
Noselite	$4Na_2O{\cdot}3Al_2O_3{\cdot}6SiO_2{\cdot}SO_4$	Hard, adherent	Tube scale
Pectolite	$Na_2O{\cdot}4CaO{\cdot}6SiO_2{\cdot}H_2O$	Hard, adherent	Tube scale
Serpentine	$3MgO{\cdot}2SiO_2{\cdot}H_2O$	Flocculent	Sludge
Sodalite	$3Na_2O{\cdot}3Al_2O_2{\cdot}6SiO_2{\cdot}2NaCl$	Hard, adherent	Tube scale
Xonotlite	$5CaO{\cdot}5SiO_2\ {\cdot}H2O$	Hard, adherent	Tube scale

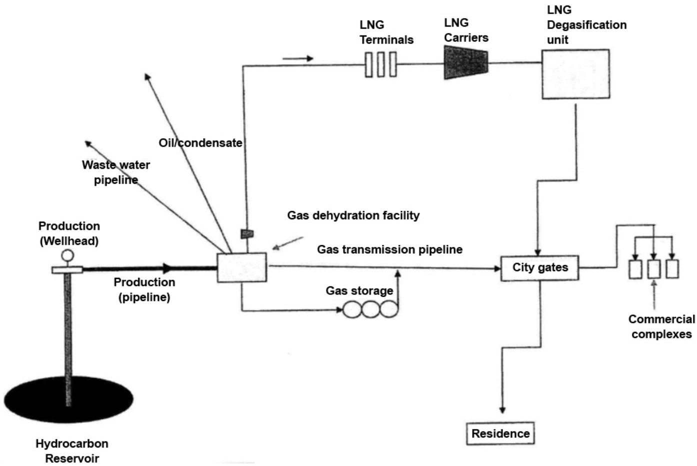
Source: J.W. McCoy, *Industrial Chemical Cleaning* (New York, NY, USA: Chemical Publishing Company, 1984). Reprinted with permission from Chemical Publishing Company.

PATHS OF CONVENTIONAL CRUDE OILS FROM WELL TO WHEEL



Source: S. Papavinasam, *Corrosion Control in the Oil and Gas Industry* (Philadelphia, PA, USA: Elsevier, 2013), p. 41.

PATHS OF NATURAL GAS FROM RESERVOIR TO THE USER



Source: S. Papavinasam, *Corrosion Control in the Oil and Gas Industry* (Philadelphia, PA, USA: Elsevier, 2013), p. 42.

PREDOMINANT CORROSION TYPES IN VARIOUS SEGMENTS OF THE OIL AND GAS INDUSTRY

Sector	Component	Predominant Material of Construction	Predominant Corrosion Type*	Main Environmental Factors Influencing Corrosion	Internal or External or Both
Production	Drill Pipe	Carbon steel	SSS Corrosion fatigue	H_2S	External
	Casing Pipe	Carbon steel	SSC	H_2S Temperature	Internal
	Casing Pipe	Carbon steel	SSC Chloride SCC	H_2S Chloride Temperature	Internal
	Downhole Tubular	Carbon steel	SSC Chloride SCC	H_2S Temperature	External
	Sucker Rods	Carbon steel	Corrosion fatigue SSC	H_2S Temperature	Internal
	Acidizing Pipe	Carbon steel	General corrosion	Acids (organic and inorganic)	Internal
	Water Generator	Carbon steel	Localized pitting corrosion	O_2 Microbes H_2S Co_2	Internal
	Gas Generator	Carbon steel	Localized pitting corrosion Chloride SCC	O_2 Chloride	Internal
	Open Mining	Carbon steel	Erosion-corrosion	Sand	Internal
	In situ Production	Carbon steel	Erosion-corrosion	Temperature Sand	Internal
	Wellhead	Carbon steel	Localized pitting corrosion SSC Localized pitting corrosion	CO_2 H_2S O_2 O_2	Internal External
	Production Pipeline	Carbon steel	HIC Localized pitting corrosion	H_2S CO_2	Internal
	Heavy Crude Oil Pipelines	Carbon steel	Localized pitting corrosion	Crude oil	Internal
	Hydrotransportation Pipeline	Carbon steel	Erosion-corrosion	Sand	Internal

Sector	Component	Predominant Material of Construction	Predominant Corrosion Type*	Main Environmental Factors Influencing Corrosion	Internal or External or Both
	Gas Dehydration Facility	Carbon steel	Localized pitting corrosion	CO_2 H_2S O_2	Internal
	Oil Separator	Carbon steel	Localized pitting corrosion	Crude oil	Internal
	Recovery Center (Extraction	Carbon steel	Erosion-corrosion	Sand Temperature	Internal
	Upgrader	See refinery			
	Lease Tank	Carbon steel	HIC Localized pitting corrosion	H_2S CO_2	Internal
	Waste Water Pipeline	Carbon steel	Localized pitting corrosion	O_2	Internal
	Tailing Pipeline	Carbon steel	Erosion-corrosion	Sand	Internal
Transmission-pipelines	Transmission Pipeline (Midstream Pipeline)	Carbon steel	SCC Localized pitting corrosion Localized pitting corrosion	CO_2 O_2 Microbes Crude oil (oil transmission) Solids-black powder (gas transmission) Microbes	Internal
	Compressor Station	Carbon steel CRAs	Erosion-corrosion Corrosion fatigue	Flow	Internal
	Pump Station	Carbon steel CRAs	Erosion-corrosion Localized pitting corrosion	Flow	Internal
	Pipeline Accessories	Carbon steel CRAs	Erosion-corrosion Localized pitting corrosion	Flow	Internal
Transportation Tankers	Ship	Carbon steel	Localed pitting corrosion MIC	Solids (sediments) Microbes Seawater Microbes	External
	LNG Tank	Carbon steel	General corrosion may occur, but corrosion is not a major issue		
	Railcar	Carbon steel	General corrosion may occur, but corrosion is not a major issue		
	Trucks	Carbon steel	General corrosion may occur, but corrosion is not a major issue		

Sector	Component	Predominant Material of Construction	Predominant Corrosion Type*	Main Environmental Factors Influencing Corrosion	Internal or External or Both
Storage	Gas Storage	Carbon steel	Localized pitting corrosion	Chloride	Internal
	Oil Storage	Carbon steel	Localize pitting corrosion MIC	Solids (sediments) Microbes Oil	Internal
				Microbes Ground water	External
Refining	Desalter	Carbon steel	Localized pitting corrosion	Salt	Internal
	Distillation units (atmospheric and vacuum)	Carbon steel	Localized pitting corrosion	Hydrochloric acid Naphthenic acid Sulfur Temperature	Internal
	Hydrotreating units	Carbon steel Stainless steel	SSC SCC Hydrogen flaking Pitting corrosion	H_2S Temperature Polythionic acid Ammonia	Internal
			Corrosion under insulation	Moisture Chlorides	External
	Catalytic reforming	Carbon steel Stainless steel	Metal dusting Carburization Pitting corrosion	Temperature Chloride Ammonia Caustic	Internal
	Catalytic cracking unit	Carbon steel Stainless steel	Intergranular SCC Erosion	Temperature Ammonia Carbonate Solid (Catalyst)	Internal
	Thermal cracking unit	Carbon steel Stainless steel	Intergranular SCC Graphitization Erosion	Temperature	Internal
	Hydro-cracking unit	Carbon steel Stainless steel	High temperature corrosion Localized pitting corrosion	H_2S Organic sulfides Temperature	Internal
	Steam cracking unit	Carbon steel	High temperature corrosion	Temperature Steam	Internal
	Visbreaker unit	Carbon steel	High temperature corrosion	Temperature	Internal
	Merox unit	Carbon steel	Localized pitting corrosion	Sulfur compounds	Internal

Sector	Component	Predominant Material of Construction	Predominant Corrosion Type*	Main Environmental Factors Influencing Corrosion	Internal or External or Both
	Coker	Carbon steel Stainless steel	High temperature corrosion (oxidation/ sulphidation)	Temperature H_2S	Internal
	Gas plant	Carbon steel	Localized pitting corrosion	Salt water	Internal
	Alkylation	Carbon steel	Localized pitting corrosion Hydrogen grooving Hydrogen embrittlement SCC Flow accelerated corrosion	Acids (sulfuric acid and hydrofluoric acid) SO_2	Internal
	Isomerization	Carbon steel	Localized pitting corrosion	Chlorides High temperature	Internal
	Gas treating plant	Carbon steel	Localized pitting corrosion	H_2S CO_2 Amines	Internal
	Sour water stripper	Carbon steel Titanium	Localized pitting corrosion Erosion-corrosion	H_2S Flow Chloride	Internal
	Claus sulfur plant	Stainless steel Carbon steel	Pitting corrosion	H_2S CO_2 SO_2 Sulfur	Internal
	Heat exchanger	Carbon steel Stainless steel Nickel alloys Titanium alloys	Pitting corrosion Erorsion-corrosion	Chloride Oxygen H_2S	Internal
	Cooling towers	Carbon steel	Localized pitting corrosion Erosion-corrosion	Chloride Oxygen	Internal
	Solvent extraction unit	Carbon steel Stainless steel	Chloride SCC	Chloride	Internal
	Steam reforming	Carbon steel	Erosion-corrosion Caustic SCC Metal dusting Corrosion fatigue	Flow Steam (water) Carbonates and bicarbonates	Internal
	MTBE	Carbon steel	Corrosion is not a major issue		

Sector	Component	Predominant Material of Construction	Predominant Corrosion Type*	Main Environmental Factors Influencing Corrosion	Internal or External or Both
	Polymerization unit	Carbon steel Stainless steel	Localized pitting corrosion	Phosphoric acid	Internal
	Other units (Hydrogen plant)	Carbon steel Stainless steel	High temperature corrosion (green rot) Localized pitting corrosion	Temperature H_2S CO_2	Internal
	Other units (ammonia plant)	Carbon steel Stainless steel	High temperature corrosion (metal dusting) SCC	High temperature CO_2 Hydrogen	Internal
Distribution	Product pipeline	Carbon steel	Corrosion is not an issue under normal operating conditions		
	Terminal	Carbon steel	Corrosion is not an issue under normal operating conditions		
	City gates and local distribution	Carbon steel	Corrosion is not an issue under normal operating conditions		
	CNG tank	Carbon steel	Corrosion is not an issue under normal operating conditions		
Special	Diluent pipeline	Carbon steel	Corrosion is not an issue under normal operating conditions		
			SCC Localized pitting corrosion	CO_2 O_2 Microbes	External
	CO_2 pipeline	Carbon steel	Localized pitting corrosion	CO_2 Impurities	Internal
	Biofuel infrastructure	Carbon steel	Stress-corrosion cracking Localized pitting corrosion	Oxygen Impurities Microbes	Internal
	High Vapor Pressure pipeline	Corrosion steel	Corrosion characteristics similar to production pipelines		
	Hydrogen pipeline	Carbon steel	Hydrogen embrittlement	Hydrogen Pressure	Internal

This does not mean that other types of corrosion do not take place, but these forms have caused major failures or incidents in these sectors.

Source: S. Papavinasam, *Corrosion Control in the Oil and Gas Industry* (Philadelphia, PA, USA: Elsevier, 2013), pp. 250-255.

COMPOSITIONS OF COMMONLY USED OIL FIELD CORROSION-RESISTANT ALLOYS

Alloy	UNS No.	Composition[(a)], wt%					
		C	Cr	Fe	Ni	Mo	Other
Alloy C-276	N10276	0.02	14.5-16.5	4-7	bal	15-17	2.5Co, 1.0Mn, 4.5W, 0.35V
Alloy 625	N06625	0.10	20-23	5	bal	8-10	0.4Al, 4.15Nb, 0.5Mn. 0.4Ti
Alloy G	N06007	0.05	21-23.5	18-21	bal	5.5-7.5	2.5Nb, 2.5Co, 2.5Cu, 2.0Mn, 1W
Alloy G-30	N06030	0.03	28-31	13-17	bal	4-6	2.4Cu, 5.0Co, 4.0W
Alloy 825	N08825	0.05	19.5-23.5	bal	38-46	2.5-3.5	0.2Al, 3Cu, 1Mn, 1.2Ti
Alloy 925	N09925	0.03	19.5-23.5	20	38-46	2.5-3.5	0.1-0.5Al, 1.9-2.4Ti
Alloy 2550	N06975	0.03	23-26	bal	47-52	5-7	0.7-12.Cu, 0.7-1.5Ti
Alloy 718	N07718	0.08	17-21	bal	50-55	2.8-3.3	0.8Al, 0.6-1.1Ti, 4.8-5.5Nb
Alloy 725	N07725	0.03	19-22.5	bal	55-59	7-9.5	0.35Al, 2.75-4Ti
Alloy 400	N04400	0.3	...	2.5	63-70	...	bal Cu, 2Mn
Alloy K500	N05500	0.2	...	2.0	63-70	...	bal Cu, 3Al, 0.85Ti
MP35N	R30035	0.025	19-21	1.0	33-37	9-10.5	bal Co, 0.15Mn. 1Ti
AL6XN	N08367	0.03	20-22	bal	23.5-25.5	6-7	0.18-0.25N
Alloy 28	N08028	0.03	26-28	bal	29.5-32.5	3-4	1.4Cu, 2.5Mn
Alloy 255	S32550	0.04	24-27	bal	4.5-6.5	2-4	2.5Cu, 1.5Mn, 0.25N
Alloy 100 (ASTM A351)	S32760	0.03	55	bal	6-8	3-5	0.7Cu, 0.25N, 0.7W
Alloy 2507	S32750	0.03	24-26	bal	6-8	3-5	0.5Cu, 0.24-0.32N
Alloy 2205	S31803	0.03	21-23	bal	4.5-6.5	2.5-3.5	0.08-0.2N
254SMO	S31254	0.02	19.5-20.5	bal	17.5-18.5	6.0-6.6	0.18-0.22N, 0.5-1.0Cu
Type 316	S31600	0.08	16-18	bal	10-14	2-3	...
654SMO	S32654	0.03	24	bal	22	7	0.5N, 0.5Cu
13Cr (Hyper 1)	...	...	13	bal	4	1.5	...
13Cr (Hyper 2)	...	...	13	bal	5	2.15	...
F6NM	S42400	0.06	12-14	bal	3.5-4.5	0.3-0.7	...
Type 420 (13Cr)	S42000	0.15	12-14	bal	...	...	...

(a) Maximum unless range is given or otherwise indicated

Source: S.D. Cramer, B.S. Covino, Jr., *ASM Handbook Volume 13C: Corrosion: Environments and Industries* (Materials Park, OH, USA: ASM International, 2006), p. 755.

DIMENSIONS OF SEAMLESS AND WELDED WROUGHT STEEL PIPE

(All dimensions are in inches)

		Norminal Wall Thickness																
NPS Desig-nator	Outside Diameter	Sche-dule 5S	Sche-dule 10S	Sche-dule 10	Sche-dule 20	Sche-dule 30	Sche-dule 40S	Stan-dard Wall	Sche-dule 40	Sche-dule 60	Sche-dule 80S	Extra Strong	Sche-dule 80	Sche-dule 100	Sche-dule 120	Sche-dule 140	Sche-dule 160	Double Extra Strong
1/8	0.405	-	0.049	-	-	-	0.068	0.068	0.068	-	0.095	0.095	0.095	-	-	-	-	-
1/4	0.540	-	0.065	-	-	-	0.088	0.088	0.088	-	0.119	0.119	0.119	-	-	-	-	-
3/8	0.675	-	0.065	-	-	-	0.091	0.091	0.091	-	0.126	0.126	0.126	-	-	-	-	-
1/2	0.840	0.065	0.083	-	-	-	0.109	0.109	0.109	-	0.147	0.147	0.147	-	-	-	0.188	0.294†
3/4	1.060	0.065	0.083	-	-	-	0.113	0.113	0.113	-	0.154	0.154	0.154	-	-	-	0.219	0.308†
1	1.315	0.065	0.109	-	-	-	0.133	0.133	0.133	-	0.179	0.179	0.179	-	-	-	0.250	0.358†
1 1/4	1.660	0.065	0.109	-	-	-	0.140	0.140	0.140	-	0.191	0.191	0.191	-	-	-	0.250	0.382†
1 1/2	1.900	0.065	0.109	-	-	-	0.145	0.145	0.145	-	0.200	0.200	0.200	-	-	-	0.281	0.400†
2	2.375	0.065	0.109	-	-	-	0.154	0.154	0.154	-	0.218	0.218	0.218	-	-	-	0.344	0.436†
2 1/2	2.875	0.083	0.120	-	-	-	0.203	0.203	0.203	-	0.276	0.276	0.276	-	-	-	0.375	0.522†
3	3.500	0.083	0.120	-	-	-	0.216	0.216	0.216	-	0.300	0.300	0.300	-	-	-	0.438	0.600†
3 1/2	4.000	0.083	0.120	-	-	-	0.226	0.226	0.226	-	0.318	0.318	0.318	-	-	-	-	-
4	4.500	0.083	0.120	-	-	-	0.237	0.237	0.237	-	0.337	0.337	0.337	-	0.438	-	0.531	0.674†
5	5.563	0.109	0.134	-	-	-	0.258	0.258	0.258	-	0.375	0.375	0.375	-	0.500	-	0.625	0.750†
6	6.625	0.109	0.134	-	-	-	0.280	0.280	0.280	-	0.432	0.432	0.432	-	0.562	-	0.719	0.864†

NPS Designator	Outside Diameter	Schedule 5S	Schedule 10S	Schedule 10	Schedule 20	Schedule 30	Schedule 40S	Standard Wall	Schedule 40	Schedule 60	Schedule 80S	Extra Strong	Schedule 80	Schedule 100	Schedule 120	Schedule 140	Schedule 160	Double Extra Strong
8	8.625	0.109	0.148	-	0.250	0.277	0.322	0.322	0.322	0.406	0.500	0.500	0.500	0.594	0.719	0.812	0.906	0.875†
10	10.750	0.134	0.165	-	0.250	0.307	0.365	0.365	0.365	0.500	0.500	0.500	0.594	0.719	0.844	1.000	1.125	1.000
12	12.750	0.156	0.180	-	0.250	0.330	0.375	0.375†	0.406	0.562	0.500	0.500†	0.688	0.844	1.000	1.125	1.312	1.000
14	14.000	0.156*	0.188*	0.250	0.312	0.375	-	0.375	0.438	0.594	-	0.500†	0.750	0.938	1.094	1.250	1.406	-
16	16.000	0.165*	0.188*	0.250	0.312	0.375	-	0.375	0.500	0.656	-	0.500	0.844	1.031	1.219	1.438	1.594	-
18	18.000	0.165*	0.188*	0.250	0.312	0.438	-	0.375†	0.562	0.750	-	0.500†	0.938	1.156	1.375	1.562	1.781	-
20	20.000	0.188*	0.218*	0.250	0.375	0.500	-	0.375	0.594	0.812	-	0.500	1.031	1.281	1.500	1.750	1.969	-
22	22.000	0.188*	0.218*	0.250	0.375	0.500	-	0.375	0.625	0.875	-	0.500	1.125	1.375	1.625	1.875	2.125	-
24	24.000	0.218*	0.250*	0.250	0.375	0.562	-	0.375	0.688	0.969	-	0.500†	1.219	1.531	1.812	2.062	2.344	-
26	26.000	-	-	0.312	0.500	-	-	0.375†	-	-	-	0.500	-	-	-	-	-	-
28	28.000	-	-	0.312	0.500	0.625	-	0.375†	-	-	-	0.500	-	-	-	-	-	-
30	30.000	-	-	0.312	0.500	0.625	-	0.375†	-	-	-	0.500	-	-	-	-	-	-
32	32.000	-	-	0.312	0.500	0.625	-	0.375†	0.688	-	-	0.500	-	-	-	-	-	-
34	34.000	-	-	0.312	0.500	0.625	-	0.375†	0.688	-	-	0.500	-	-	-	-	-	-
36	36.000	-	-	0.312	0.500	0.625	-	0.375†	0.750	-	-	0.500	-	-	-	-	-	-

For tolerances on outside diameter and wall thickness see appropriate specifications. Schedule 5S, 10S, 40S and 80S apply to austenitic chromium-nickel steel pipe only.

Except when marked † Standard, Extra Strong and Double Extra Strong wall thicknesses have pipe of corresponding wall thickness listed under one of the schedule numbers. Dimensions in this table are abstracted from ASA Standard B36.10 and ASA Standard B36.19, except that wall thicknesses marked* do not appear in ASA Standard B36.19.

STANDARD WALL STEEL PIPE DIMENSIONS, CAPACITIES, AND WEIGHTS

NPS Designator	Outside Diameter in.	Wall Thickness in.	Inside Diameter in.	Cross Sectional Area of Metal in.^{2}	Circumference, ft. or Surface Area ft.^{2}/ft. of length Outside	Inside	Capacity at 1 ft./s Velocity U.S. Gal. per min.	Weight of Pipe lb./ft.
1/8	0.405	0.068	0.269	0.072	0.106	0.0705	0.179	0.25
1/4	0.540	0.088	0.364	0.125	0.141	0.0954	0.323	0.43
3/8	0.675	0.091	0.493	0.167	0.177	0.1293	0.596	0.57
1/2	0.840	0.109	0.622	0.250	0.220	0.1630	0.945	0.85
3/4	1.050	0.113	0.824	0.333	0.275	0.2158	1.665	1.13
1	1.315	0.133	1.049	0.494	0.344	0.2745	2.690	1.68
1 1/4	1.660	0.140	1.380	0.669	0.435	0.362	4.57	2.28
1 1/2	1.900	0.145	1.610	0.799	0.498	0.422	6.34	2.72
2	2.375	0.154	2.067	1.075	0.622	0.542	10.45	3.66
2 1/2	2.875	0.203	2.469	1.704	0.753	0.647	14.92	5.80
3	3.500	0.216	3.068	2.228	0.917	0.804	23.00	7.58
3 1/2	4.000	0.226	3.548	2.680	1.047	0.930	30.80	9.11
4	4.500	0.237	4.026	3.173	1.178	1.055	39.6	10.8
5	5.563	0.258	5.047	4.304	1.456	1.322	62.3	14.7
6	6.625	0.280	6.065	5.584	1.734	1.590	90.0	19.0
8	8.625	0.322	7.981	8.396	2.258	2.090	155.7	28.6
10	10.750	0.365	10.020	11.90	2.814	2.620	246.0	40.5
12	12.750	0.375	12.000	14.58	3.338	3.142	352.5	49.6
14	14.000	0.375	13.250	16.05	3.665	3.469	430.0	54.6
16	16.000	0.375	15.250	18.41	4.189	3.992	568.0	62.6
18	18.000	0.375	17.250	20.76	4.712	4.516	728.4	70.6
20	20.000	0.375	19.250	23.12	5.236	5.040	902.0	78.6
22	22.000	0.375	21.250	25.48	5.760	5.563	1105.	86.6
24	24.000	0.375	23.250	27.83	6.283	6.087	1325.	94.6
26	26.000	0.375	25.250	30.19	6.807	6.610	1561.	102.6
28	28.000	0.375	27.250	32.54	7.330	7.134	1818.	110.6
30	30.000	0.375	29.250	34.90	7.854	7.658	2094.	118.7
32	32.000	0.375	31.250	37.26	8.378	8.181	2391.	126.7

NPS Designator	Outside Diameter in.	Wall Thickness in.	Inside Diameter in.	Cross Sectional Area of Metal in.^{2}	Circumference, ft. or Surface Area ft.^{2}/ft. of length Outside	Inside	Capacity at 1 ft./s Velocity U.S. Gal. per min.	Weight of Pipe lb./ft.
34	34.000	0.375	33.250	39.61	8.901	8.705	2706.	134.7
36	36.000	0.375	35.250	41.97	9.424	9.228	3042.	142.7
METRIC CONVERSION FACTORS								
-	×25.4	×25.4	×25.4	×645.	×0.305	×0.305	×0.01242	×1.488
	=mm	=mm	=mm	=mm^2	=m^2/m	=m^2/m	= m^3/min. at 1 m/s	=kg/m