CORROSION DAMAGE AND DEGRADATION

N. Mary (09.2023 – Tohoku Univ.)

SOMMAIRE

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3. CORROSION TESTING, MONITORING, INSPECTION

4. CORROSION PREVENTION

- **INTRODUCTION OF DAMAGE AND DEGRADATION**

DEFINITION

Several definitions of corrosion have been given by the past, all of them use words as:

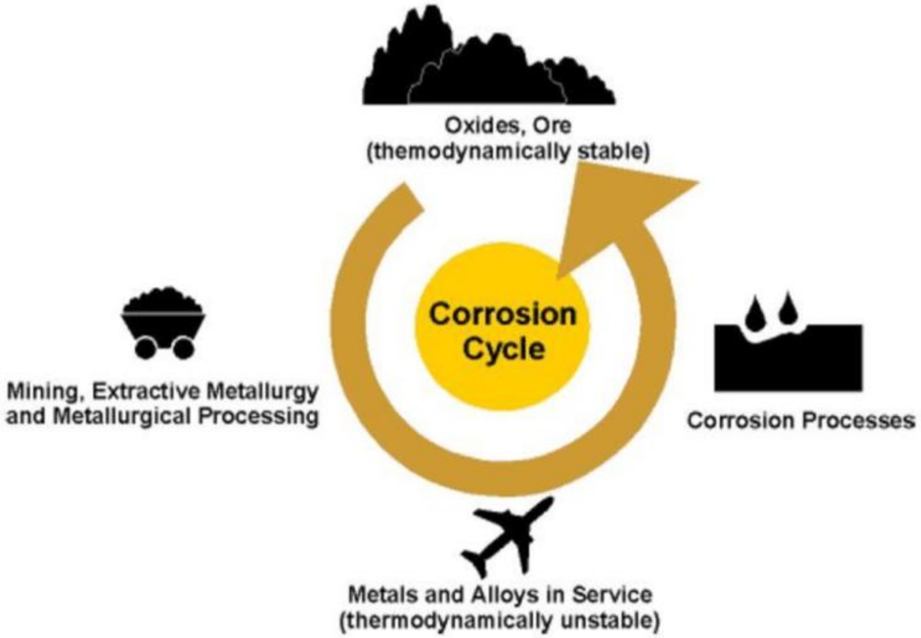
- deterioration / degradation / destructions / attack
- Environments
- interactions

➔ Corrosion is basically the result of interaction between materials and their environment. Consequently, the material losses some of its properties (mechanical, physical, chemical) and fails

In some forms of corrosion, there is almost no visible weight change of degradation, yet properties change and material fail. This changes defy ordinary visual examination of weight change determinations.

DEFINITION

The corrosion is a part of a cycle of life of an element



Corrosion-club, 2007

DEFINITION

Three questions must be asked to answer corrosion issues:

- Corrosion by environment. All the environments are corrosive to some degree
- Corrosion of metal (ferrous non-ferrous)
- How is it corroded: shape, morphology, location of the corrosion defect.

All materials are sensitive to degradation.

However, corrosion is often (almost all the time) limited to metallic material

Nonferrous metals corrode but do not rust

Nonmetals are excluded to the definition :

Plastic swell or cracks, Wood split or decay, Portland cement leach away

CONSEQUENCE OF CORROSION

Somes corrosion consequences:

- Plant shutdows → industry and consumer problems
- leaking container, storage tanks… → loss of product and generation of severe accidents and hazards (at least 25% of drinkable water is lost by leakage
- Loss of efficiency. Insulation of heat exchanger tubings and pipelines by corrosion products reduces heat transfer and piping capacity
- Contamination. Corrosion products may contaminate chemicals, pharmaceuticals dyes…
- Nuclear hazards. Transport of radioactive corrosion products in water fatal to biological life

Magnitude of corrosion would depend upon the sensitivity of a particular metal or alloy to a specific environment.

Ex. Copper corrodes rapidly in the presence of ammonia givens serious problem in agriculture areas.

CONSEQUENCE OF CORROSION

The consequence of the corrosion determine the priority of maintenance activities or improvement required to prevent its occurrence.

The failure consequences are grouped into 4 categories:

Operational consequences. Has the failure any direct adverse effect on operational capability?

Safety consequences. Does the corroded pieces cause an immediate loss of function or secondary damage?

Nonoperational consequences. Example of navigation unit in plane equipped with redundant navigation system

Hidden failure consequences. No direct adverse effect but increase exposure to consequences of multiple failure

COST OF CORROSION

In average 4-5 % of Gross Domestic Product for most of the industrialized nation.

Some startling figures of corrosion losses

- Corrosion cost of gas and liquid transmission pipelines
- Corrosion free life of automobile in the coastal regions of arabian gulf = 6 months
- 95% of concrete damage in arbian gulf coastal region is caused by reinforcement corrosion and consequent spalling of concrete
- 10% of all aircraft maintenance in USA is spent on corrosion remediation

COST OF CORROSION

Indirect losses due to corrosion:

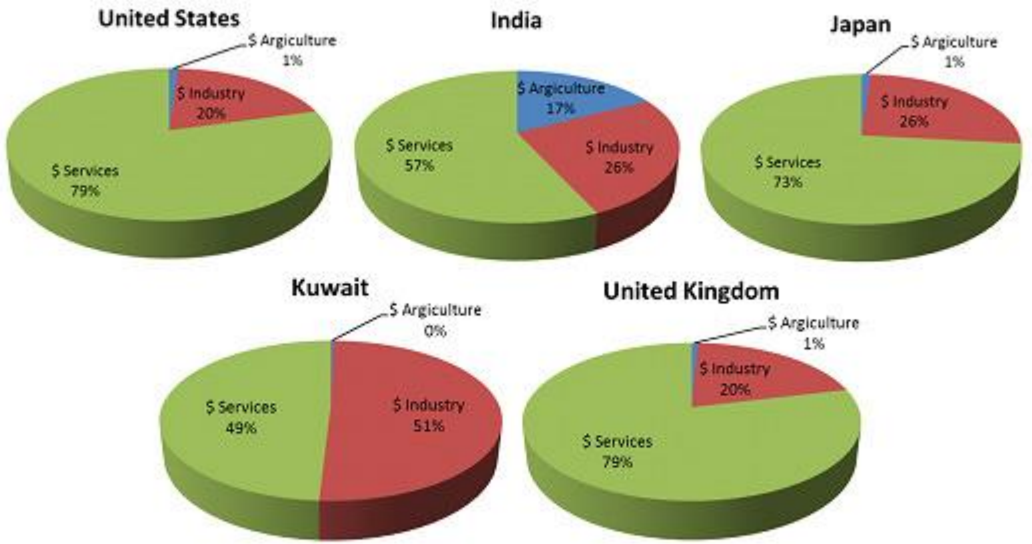
- Lost of efficiency
- Lost of production
- Product contamination
- Shutdown
- overdesign

Direct losses:

- Material cost
- Maintenance
- Human power

COST OF CORROSION

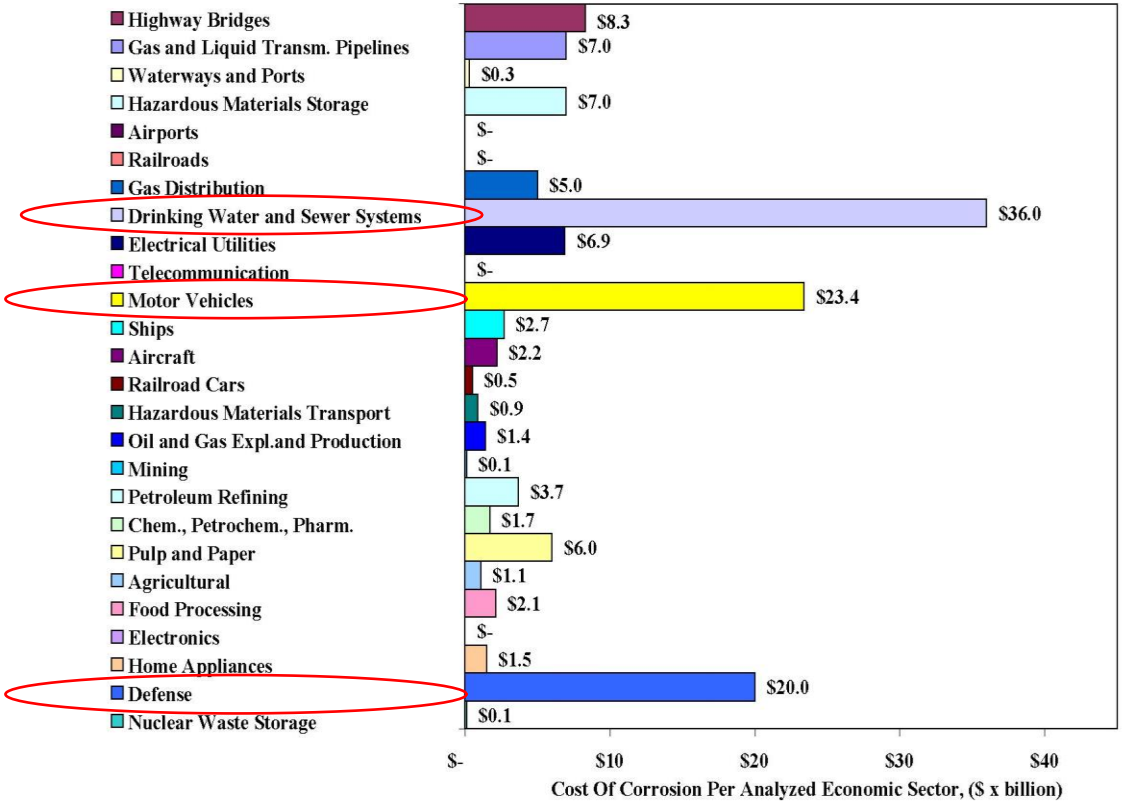
The cost of corrosion differs from country to country



Nace international impact report 2016

COST OF CORROSION

The cost of corrosion penetrates all industries



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CORROSION SCIENCE & ENGINEERING

Corrosion may severely affect the following functions of metals, plants and equipments:

- Impermeability. Environmental constituents must not be allowe to enter pipes, process, food containers... to minimize the possibility of corrosion
- Mechanical strength. Corrosion should not affect the capability of withstand specified loads.
- Dimensional integrity (maintaining design dimensions)
- Physical properties (thermal conductivity, electrical properties)
- Contamination of environment
- Damage to other equipment. Adjacent equipment may not be damage by a corrosion failure

➔ Safety, Health, depletion of resources, appearances and cleanliness, product life, restoration of corroded objects

CORROSION SCIENCE & ENGINEERING

Corrosion scientist studies tend to :

- Improve the understanding the cause of corrosion
- Find ways to prevent or minimize damages caused by corrosion

Corrosion engineer tends to :

- Apply knowledge to control corrosion

Explanations :

Cor. Eng. → use cathodic protection to prevent buried pipelines corrosion

Cor. Sc. → test and develops new protective solutions (paint, corrosion inhibitors,…)

➔ Both Eng. & Sci. viewpoints are necessary in the diagnosis of corrosion damage and remediation

CORROSION SCIENCE & ENGINEERING

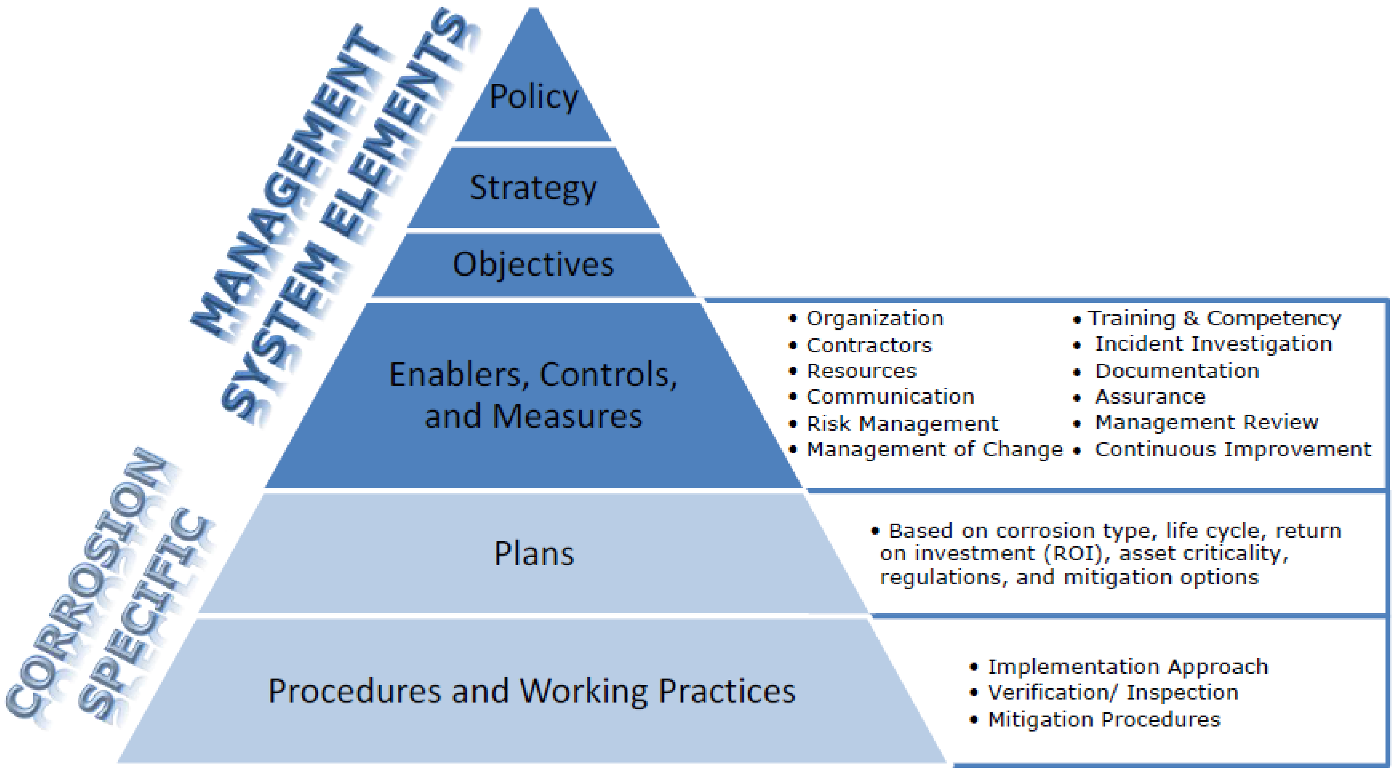

Figure 3-3. Hierarchy of General and Corrosion-Specific Management Elements

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CORROSION SCIENCE & ENGINEERING

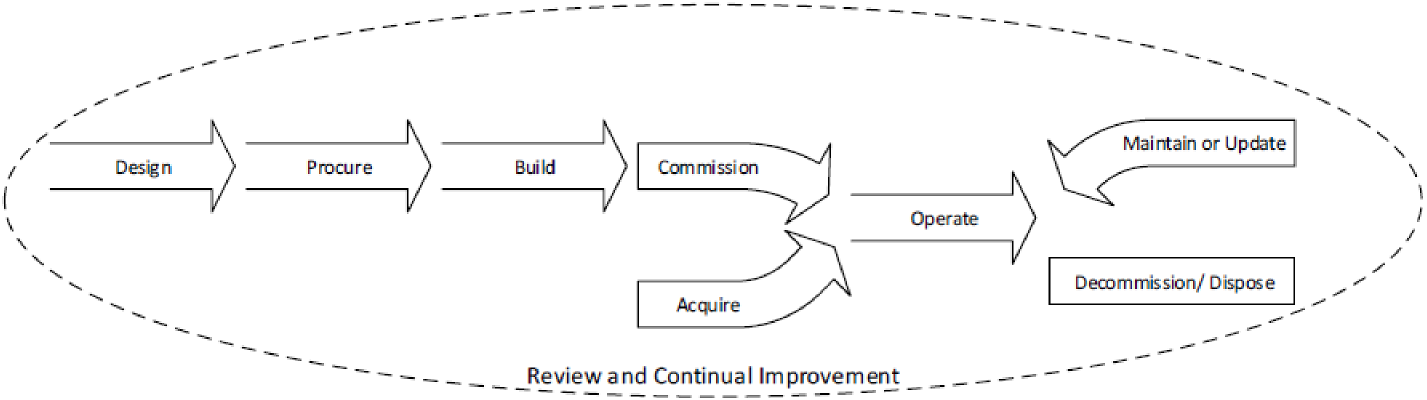

Figure 3-5. Corrosion Management over the Life Cycle of the Asset

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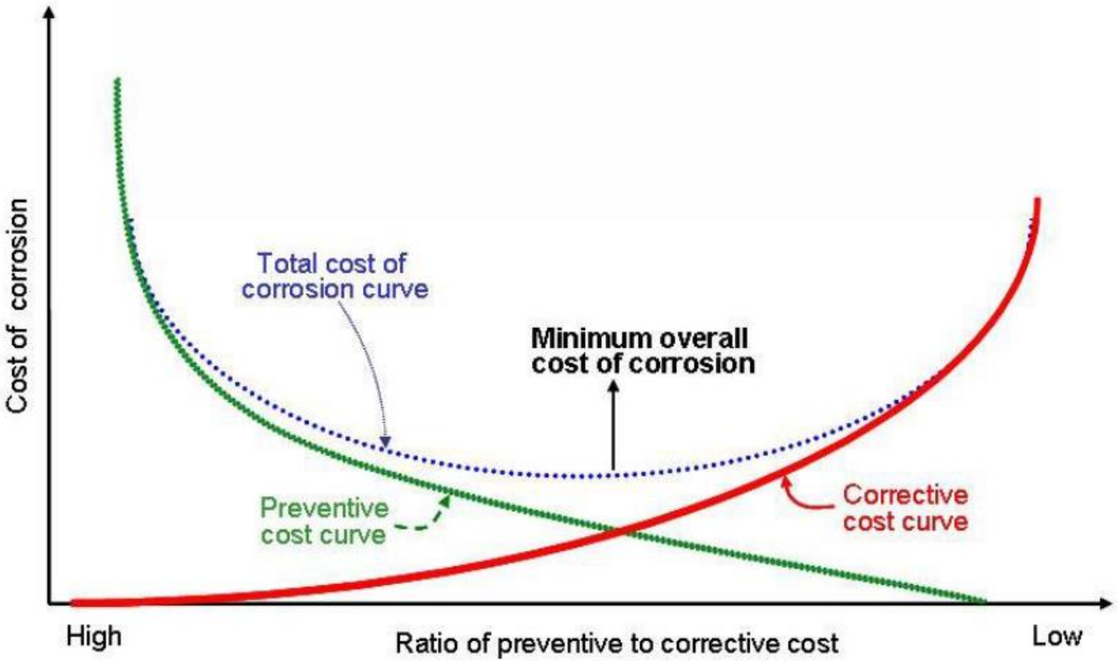

Figure E-1. Preventive and Corrective Corrosion Cost Curves

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CORROSION SCIENCE & ENGINEERING

Risk is defined as the probability P of an occurrence multiplied by the consequence C of the occurrence : $R = P \times C$

Here P = corrosion-related failure,

C is measured in financial terms: total cost of a corrosion failure, including the replacement, clean-up, repair…)

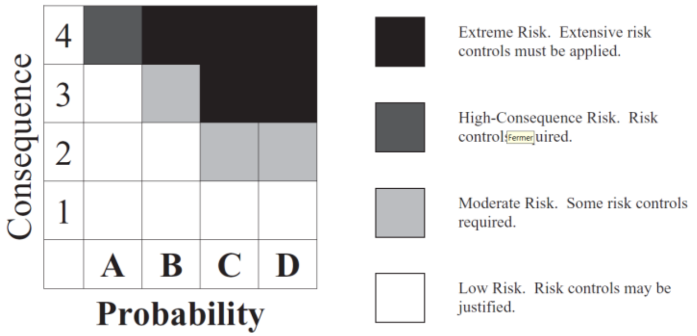

Figure 1.1. A simplified approach to risk management, indicating qualitatively the areas of high risk, where both consequence and probability are high.

Managing corrosion is a part of the risk management

- RM must be included in the design stage
- Maintenance must be carried out
  ➔risk continues to be managed
- Engineering design must include corrosion control equipment
  ➔corrosion monitoring → risk managed during the operational lifetime

Corrosion and corrosion control. R.W. Revie, H.H. Uhlig, (2007)

FIVES GOOD REASONS TO STUDY CORROSION

- Material resources consumption
  - Shortage of some rare materials

- Engineering knowledge is incomplete without understanding corrosion
  - Planes, ships, automobile are moving in aggressive environments

- Corrosion has been a very important in several engineering disasters

- Designing of artificial implants

- Corrosion is a threat to the environment

BETTER CORROSION MANAGEMENT

- Be aware of corrosion costs and potential savings
- Something can be done about corrosion
- Promote corrosion management in polities, regulation, standards and practices
- Educate and train staff in recognition of corrosion control
- Develop advance corrosion control technologies (research, development, implementation)

FORMS OF CORROSION

8 general types of corrosion. Classification according the appearance

Type of Corrosion	Material System	Driving Force	Control Point	Remark
Uniform/General Corrosion	All Metals in Atmospheric Environment	- Atmospheric -Temperature	- Painting - Hot Dip Galvanizing	- Corrosion Cost of this form about 50% of the total corrosion cost - Seldom lead to failure
Intergranular Corrosion	Al Alloys, Ni-Cr Austenitic Stainless Steel Acids Containing Oxidizing Agents (sulfuric, phosphoric), Hot Organic Acid. High Cl Content Seawater	-Third Phase Precipitate - Temperature	- Heat Treatment in Manufacturing - Welding during Fabrication	- Loss of Strength and Ductility - Severe attack can lead to failure
Galvanic Corrosion	Galvanic Coupling Materials e.g. Fe with Cu, Carbon steel with Stainless Steel	Different Metal in electrolytic solution	- Proper Design; - Rivetting/Joining Materials; - Insulating Coupling Materials	Moderate effect but can be detrimental for a longer period
Crevice Corrosion	Metal to Metal/Non Metal in Electrolyte Metal in two Electrolyte Aluminium and Stainless Steel in Seawater	- Small Gap in electrolyte (<3,18mm) - Stagnant Fluid	- Proper Design - Gasketting Materials -Proper Drainage Practice	Moderate effect but can be detrimental for a longer period
Pitting	Stainless Steel and Aluminium in cloride or bromide environment (water/soils)	- Surface Irregularities - Presence of Cl or Br Ion - Chemical Composition - Temperature	- Surface Quality Control - Proper Welding Practice -Proper Material Handling - PREN (Material Selection) - CPT (Critical Pitting Temperature)	Severe attack can lead to failure (second biggest corrosion failure)
Erosion Corrosion Tribo-Corrosion	Carbon Steel, Stainless Steel in flowing fluid containing abrasives	Synergy effect of passive film breakdown by abrasive and localized corrosion	Corrodent; turbulency Corrodent impingement in elbow and tees	Severe attack can lead to failure
Stress Corrosion Cracking (SCC)/ HE-SCC	Stainless Steel, Carbon Steel in High pH (pH >9,3) - 600 - 750 mV - Temperature Sensitive Near Netral pH (5,5 - 7,5) - Free Potential - Non-Temperature Sensitive	- Microstructure - Temperature Region - Existence of Residual Stress - Suitable pH - Presence of H_2S, Chloride ion -Residual Stress	- Microstructure Control during - H_2S Content & Temperature - Operation Temperature	-Biggest Cause of Corrosion Failure -SCC found in gas and liquid pipelines - In Canada since 1977: recorded 22 catastrophic failure (12 rupture, 10 leaks)
Biological Corrosion/ Microbial Induced Corrosion	All Metals in Environment with: - Sulfate Reducing Bacteria - Sulphur/Sulfate Oxidizing Bacteria - Fe/Mn Oxidizing Bacteria - Organic Acid Producing Bacteria	- Gravitational & Pellicular Water - pH 6 - 8 - Potential -42mV to 820mV - Temperature: 20 ^oC - 45 ^oC	Application of Organic Coating Cleaning Practice Use of Biocide	In US, $1.2 billion SPENT annually on biocidal chemicals to fight MIC.

Stemp et al. Corrosion Science (2003)

FORMS OF CORROSION

8 general types of corrosion

Type of Corrosion	Driving Force
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Intergranular Corrosion	-Third Phase Precipitate - Temperature
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Stress Corrosion Cracking (SCC)/ HE-SCC	- Microstructure - Temperature Region - Existence of Residual Stress - Suitable pH - Presence of H_2S, Chloride ion -Residual Stress
Biological Corrosion/ Microbial Induced Corrosion	- Gravitational & Pellicular Water - pH 6 - 8 - Potential -42mV to 820mV - Temperature: 20 °C - 45 °C

Environmental factors:

- gas
- temperature
- ions in solution (anions and pH)

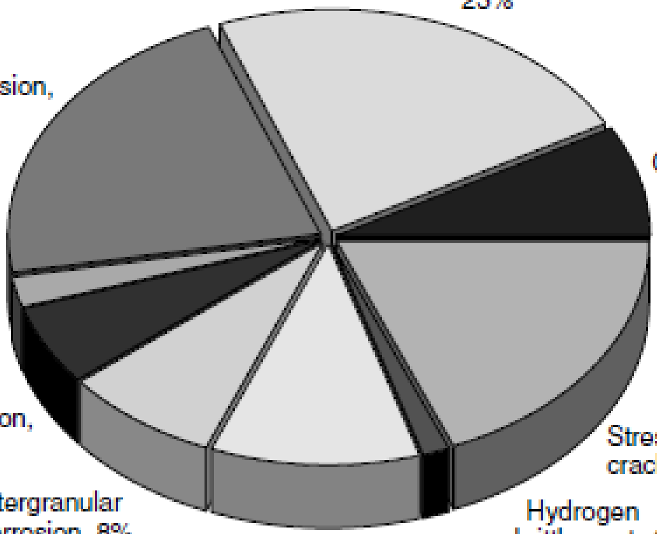
Materials factors:

- microstructure heterogeneities (defect, grain boundaries…)
- residual stresses
- applied surficial or volume loads
- chemical composition

Stemp et al. Corrosion Science (2003)

FORMS OF CORROSION

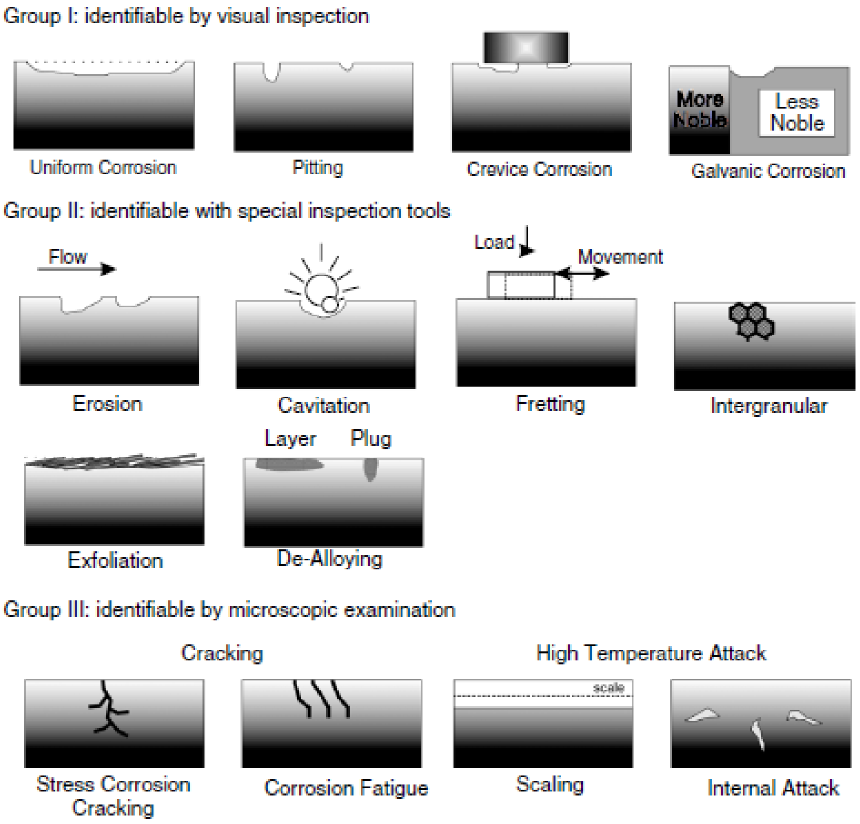
8 general types of corrosion



Corrosion Inspection and Monitoring. P. R. Roberge (2007)

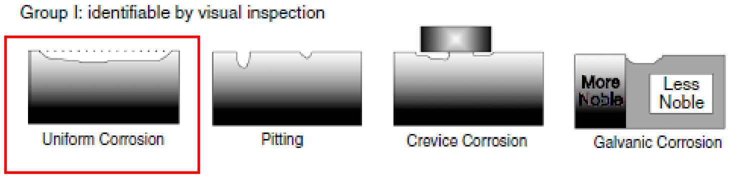
FORMS OF CORROSION

Recognition of corrosion attack



Corrosion Inspection and Monitoring. P. R. Roberge (2007)

FORMS OF CORROSION



Recognition of corrosion attack

The least threatening type of attack

Allowing one to forecast with some accuracy the probable life of equipment.

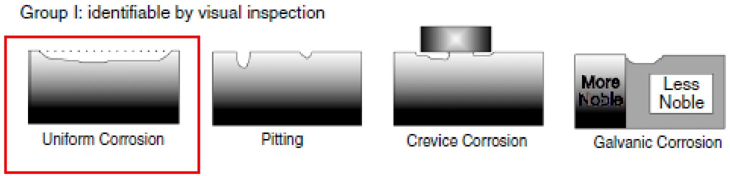
Failures of metals by rapid general attack (wasting away) are not often encountered.

uniform attack is relatively detectable and its effects predictable

Corrosion Inspection and Monitoring. P. R. Roberge (2007)

FORMS OF CORROSION

Recognition of corrosion attack



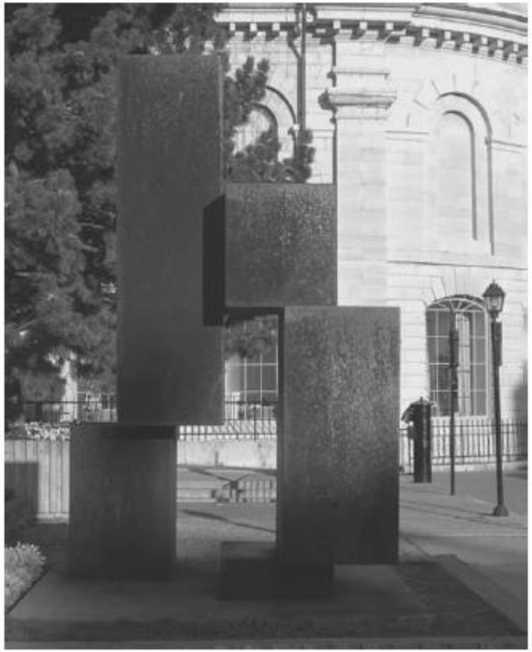


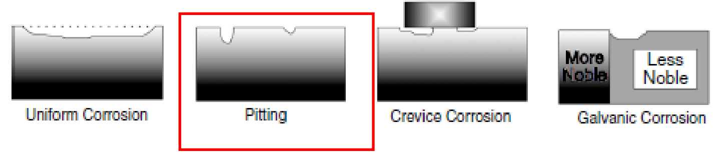
FIGURE 6.4 Outdoor sculpture besides City Hall in Kingston, Ontario.

(20 years)

Corrosion Inspection and Monitoring · Pierre R. Roberge (2007)
Corrosion Engineering Principles. E. Bardal (2004)

FORMS OF CORROSION

Pitting or localized corrosion

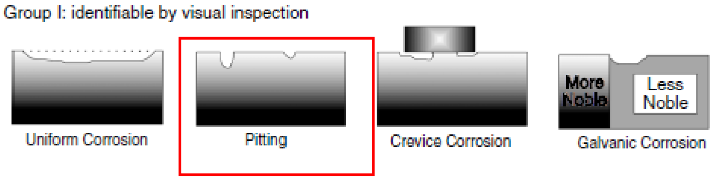


Importance of pitting corrosion is a function of the metal thickness, metallurgy and the penetration rate

Pits may be openned or corrosion products may for caps over the pit.

Corrosion Inspection and Monitoring · Pierre R. Roberge (2007)

FORMS OF CORROSION



Pitting or localized corrosion

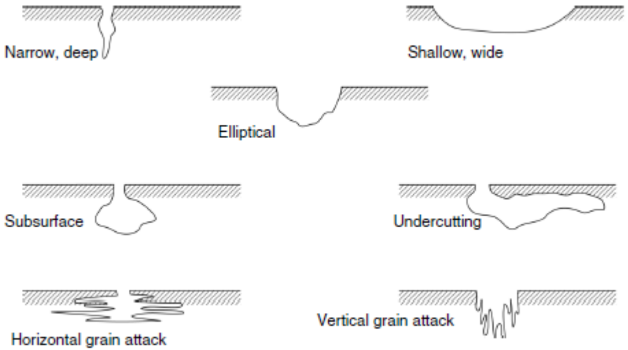


Fig. 2.8. Typical cross-sectional shapes of corrosion pits.

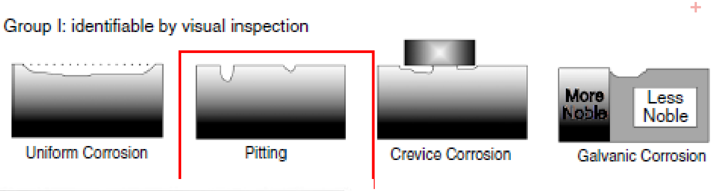
Factors contributing to initiation and progagation of pits:

- Localized chemical or mechanical damage of a protective oxide film
- Water chemistry (acidity, low [O_2]) chloride…
- Poor application of a protective coating
- Heterogeneities in the metal structure (inclusions).

Corrosion Inspection and Monitoring · Pierre R. Roberge (2007)

FORMS OF CORROSION

Pitting or localized corrosion



Complex interactions leads to major differences on how pits initiate and develop.

For Copper (water conditions):

- Type I. in hard or moderate water (7< pH < 7.8) and cold water ➔ pits are deep and narrow → pipe failure
- Type II. Soft water (pH <7.2) below 60°C. Narrow pits → pipe failure
- Type III. Cold soft water (pH>8). Wide and shallow. Pipe blockage

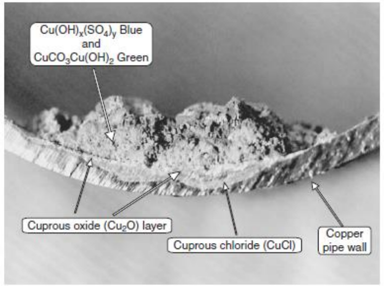
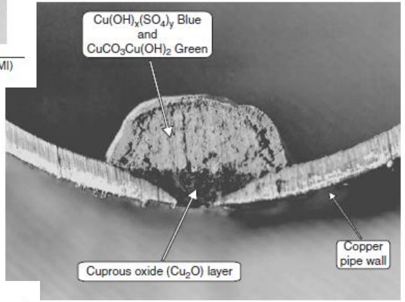


Figure 6.12 Type I copper pitting corrosion. (Courtesy of Russ Green, TMI)



13 Type II copper pitting corrosion. (Courtesy of Russ Green, TMI)

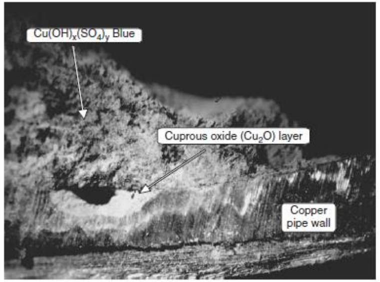
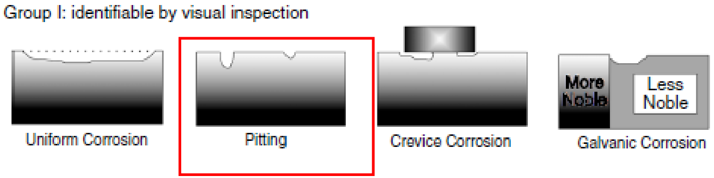


Figure 6.14 Type III copper pitting corrosion. (Courtesy of Russ Green, TMI)

Corrosion Engineering Principles Practices. E. Bardal (2004).

FORMS OF CORROSION



Pitting or localized corrosion

A pit = 4 stages :

- Initiation : local cell (anodic and cathodic area)
- Propagation . Rate increase because chemical changes
- Termination. Internal resistance increase (filming…)
- Reinitiation (after dry-wet condition)

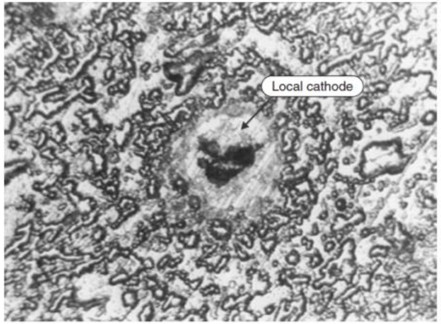
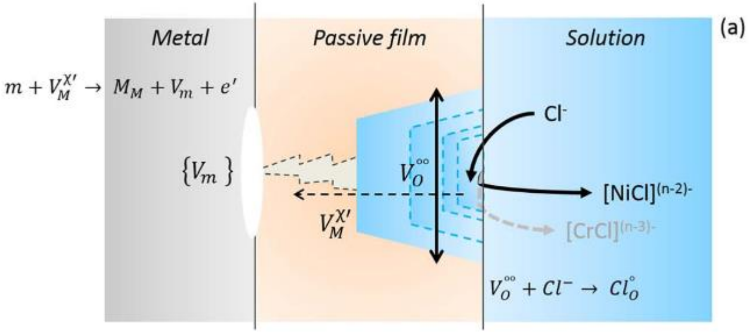


Figure 6.15 Pitted surface of aluminum A92519 exposed to a 3.5 percent NaCl solution for seven days (×100).



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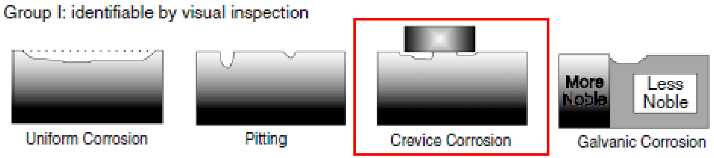
Corrosion Engineering Principles Practices. E. Bardal (2004).

FORMS OF CORROSION



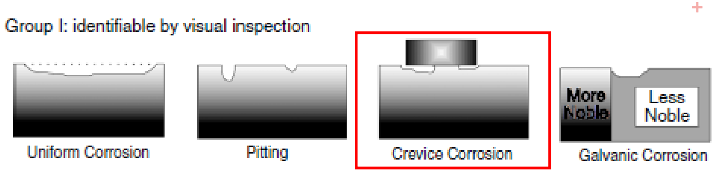
Crevice corrosion

Aggravation of localized corrosion

Crevice corrosion occurs between mating surfaces of metal assemblies
It initiates because a local chemical variation of the environment

Corrosion Inspection and Monitoring · Pierre R. Roberge (2007)

FORMS OF CORROSION



Crevice corrosion

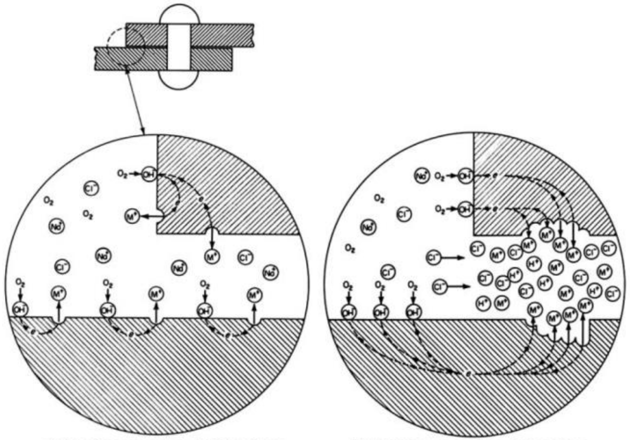


Figure 6.21 Crevice corrosion[16]

Aggravation factor comes from :

- The dissolved metal itself
- Local acidification
- Corrosion product that seal the crevice
- Positive charge accumulation attracting strongly negative ions

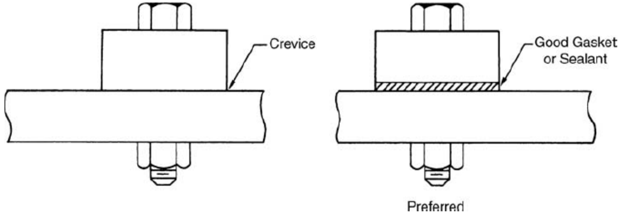
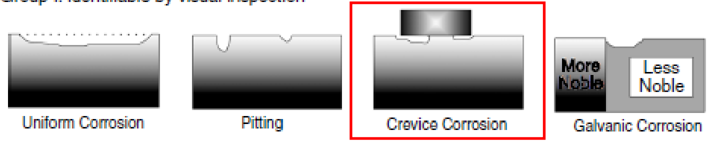


Figure 1.47 Gasket or sealant to avoid crevices

Corrosion and protection· V.S. Sastri (2007)

FORMS OF CORROSION

Recognition of corrosion attack



In 90's, average car life about 10-12 years
Scatter between manufactures
Corrosion, small areas badly designed:

- Interweld gaps and narrow capillaries (hardly accessible to electrocoat paint)
- Protruding member at right angles to the direction of motion
- Ledges and vertical panels suffer from aggravated poultice corrosion
- Raw edged covered only a thin layer of protective coating

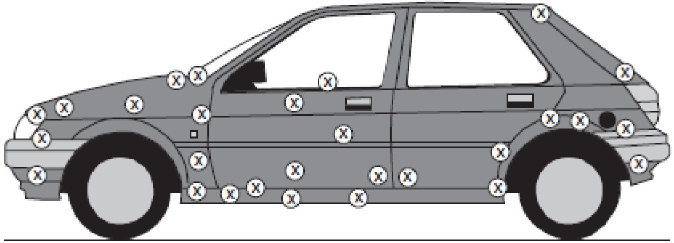


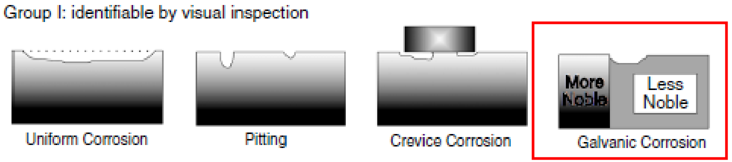
FIGURE 6.23 Diagrammatic view of corrosion prone areas in cars (adapted from [12]).

FIGURE 6.24 Sand trapped behind trim can wear away the protective paint coating and expose the steel to the environment and subsequent severe corrosion damage.

Corrosion Inspection and Monitoring · Pierre R. Roberge (2007)
Corrosion Engineering Principles. E. Bardal (2004)

FORMS OF CORROSION

Recognition of corrosion attack



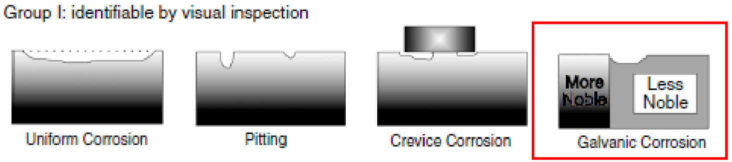
Metal	Potential V (CSE)
Commercially pure magnesium	−1.75
Magnesium alloy (6% Al, 3% Zn, 0.15% Mn)	−1.6
Zinc	−1.1
Aluminum alloy (5% Zinc)	−1.05
Commercially pure aluminum	−0.8
Mild steel (clean and shiny)	−0.5 to −0.8
Lead	−0.5
Cast iron (not graphitized)	−0.5
Mild steel (rusted)	−0.2 to −0.5
Mill scale on steel	−0.2
High silicon cast iron	−0.2
Copper, brass, bronze	−0.2
Mild steel in concrete	−0.2
Platinum	0 to −0.1
Carbon, graphite, coke C	+0.3

Galvanic corrosion = dissimilar metal corrosion

Corrosion Inspection and Monitoring · Pierre R. Roberge (2007)

FORMS OF CORROSION

Recognition of corrosion attack



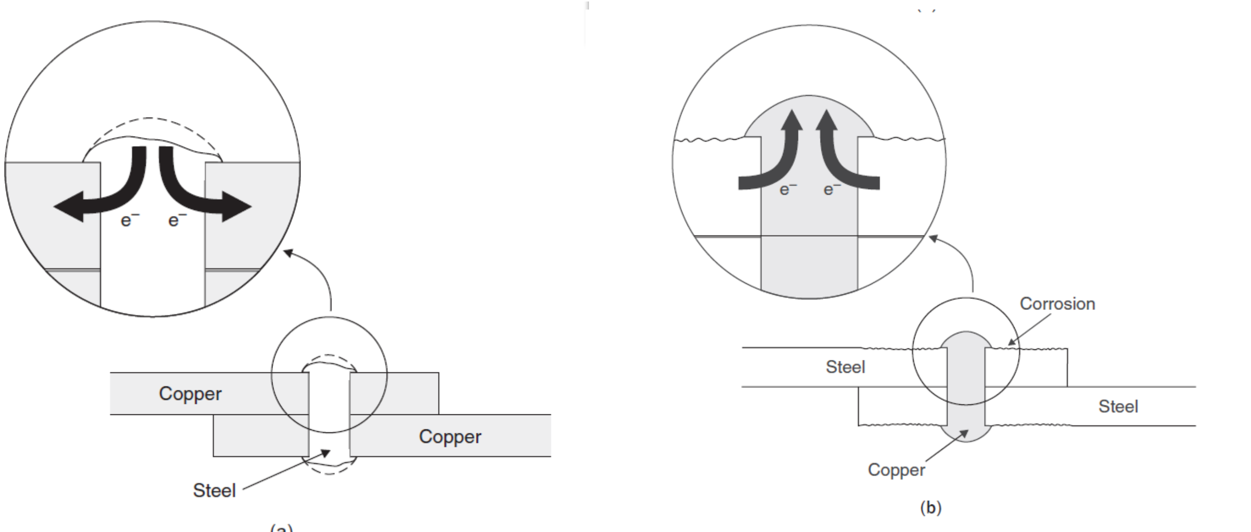


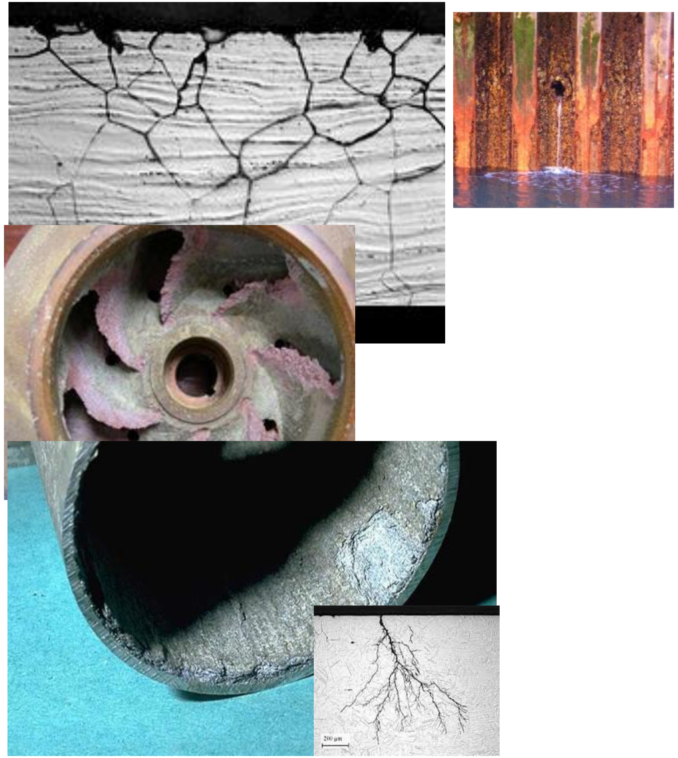
FIGURE 3.8 Galvanic coupling caused by riveting with dissimilar metals: (*a*) steel rivets on copper plates, (*b*) copper rivets on steel plates.

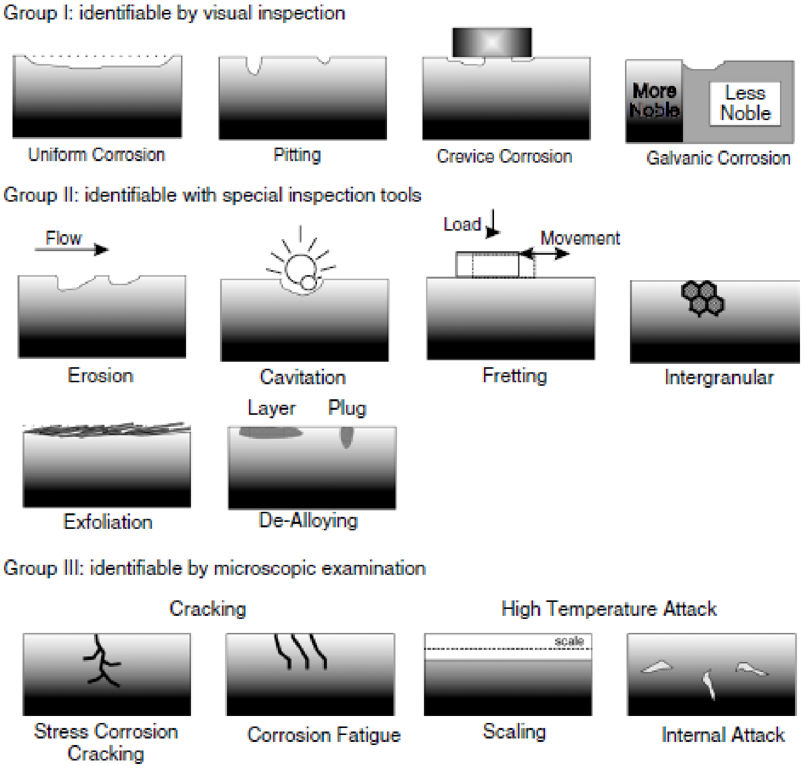
Corrosion Engineering, Principles and Practice. P.R. Roberge (2008)

FORMS OF CORROSION

Typical images for each case of corrosion

Type of Corrosion
Uniform/General Corrosion
Intergranular Corrosion
Galvanic Corrosion
Crevice Corrosion
Pitting
Erosion Corrosion Tribo-Corrosion
Stress Corrosion Cracking (SCC)/ HE-SCC
Biological Corrosion/ Microbial Induced Corrosion





Images S. Audisio le livre de la corrosion

THANK YOU FOR YOUR ATTENTION