Erosion, Erosion-Corrosion, Flow Assisted Corrosion, …

Differences and Convergences

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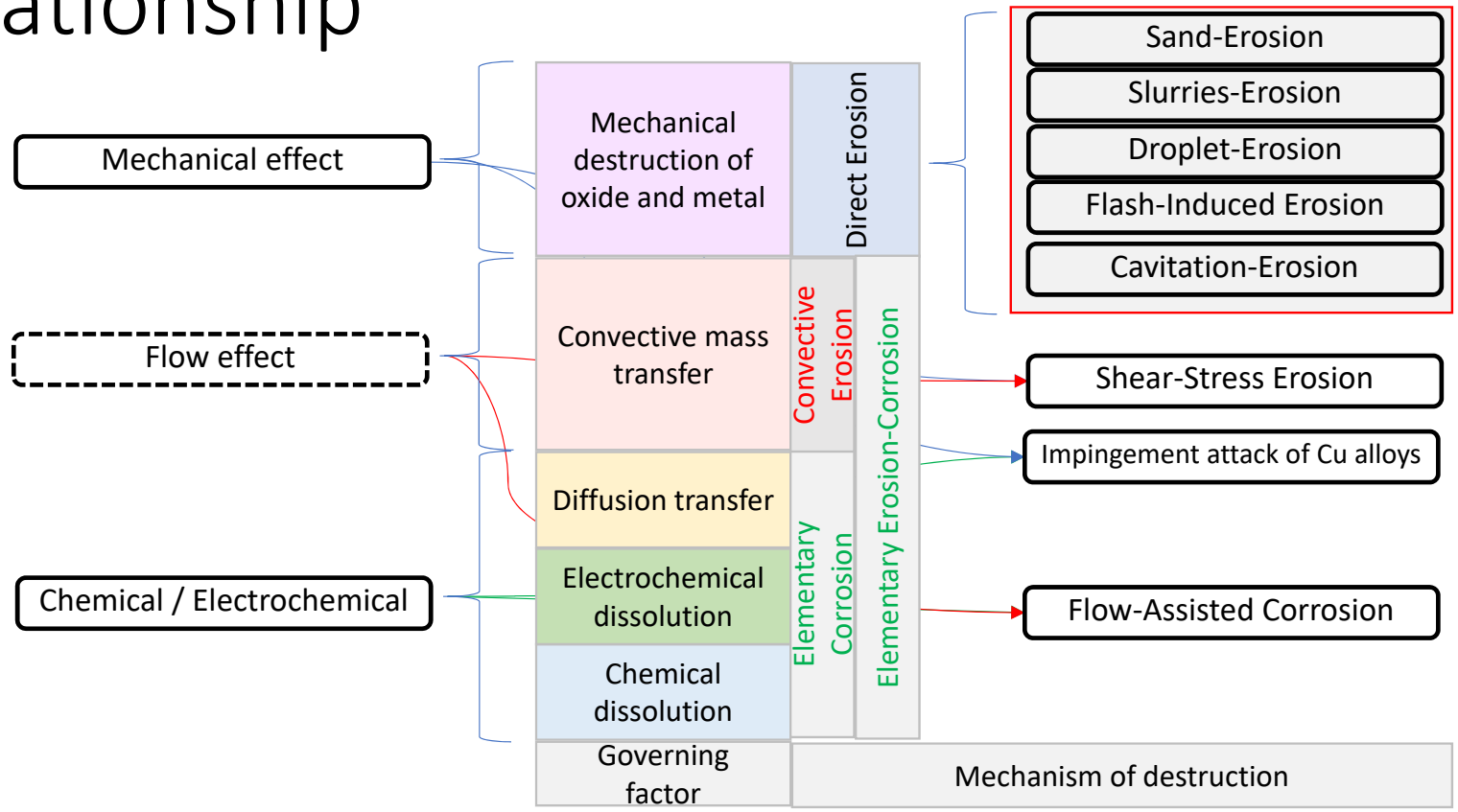
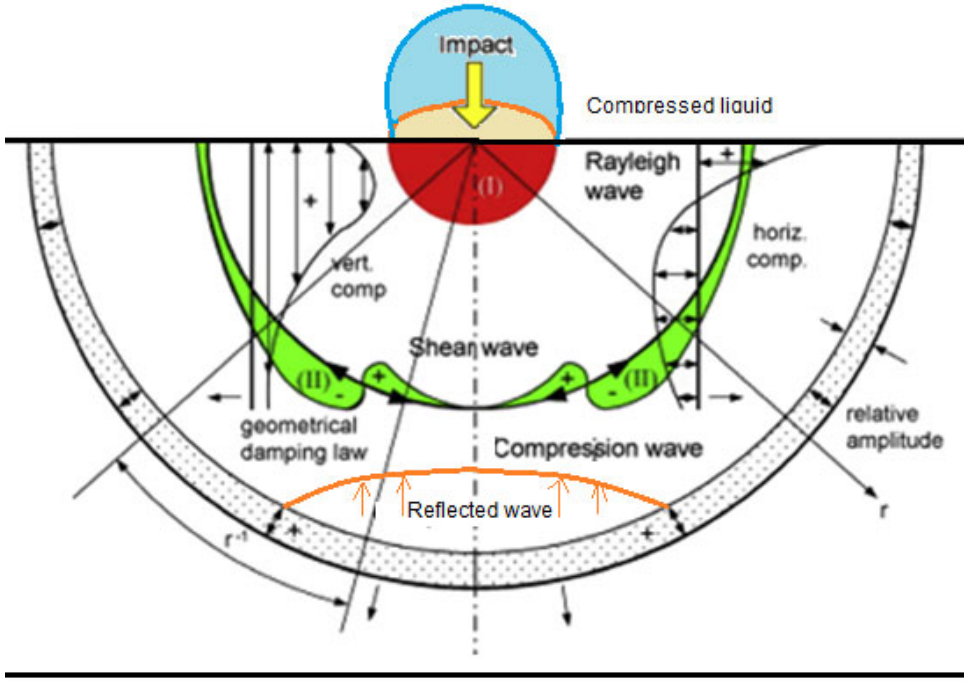
CEFRACOR – Commission Inhibiteurs et traitement des eaux 18/04/2019

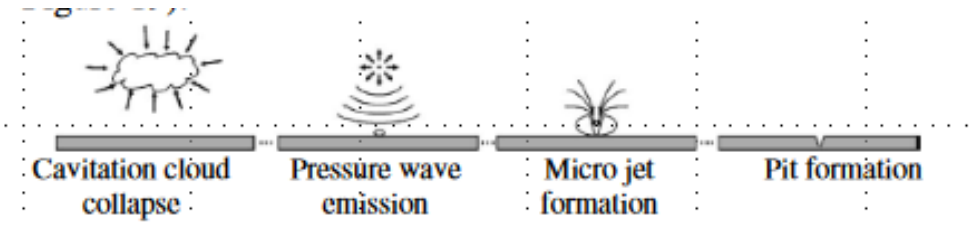
Erosion, Erosion-Corrosion, Corrosion Relationship



Droplet Impingement Erosion, Cavitation-Erosion



Liquid droplet surface impact interactions (droplet and target shockwave behavior)



Cavitation – erosion model (Dular et al, 2006)

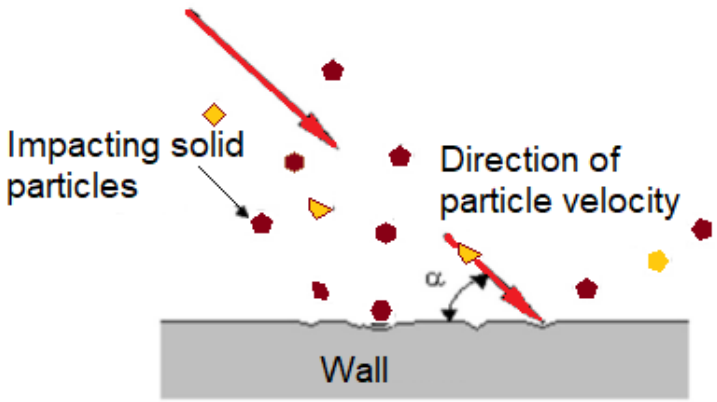
- Collapse of cavitation cloud: shock wave into the fluid
- Magnitude of shock wave attenuated towards the solid surface
- Single bubbles present close the solid surface begin to oscillate and a micro-jet phenomena will occur if the bubble is close to the wall
- Single pit damage is caused by a high velocity liquid jet impacting the solid surface

Other Models: Kato et al. (1996); **Bark et al**. (2004); **Fortes Patella et al** (2004).

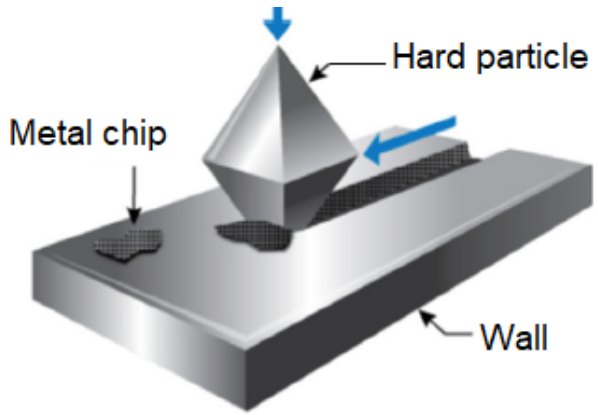
Erosion vs. target material

- Ductile material: Grooves & Chips formation without cracks
- Brittle material: Grooves & Cracks

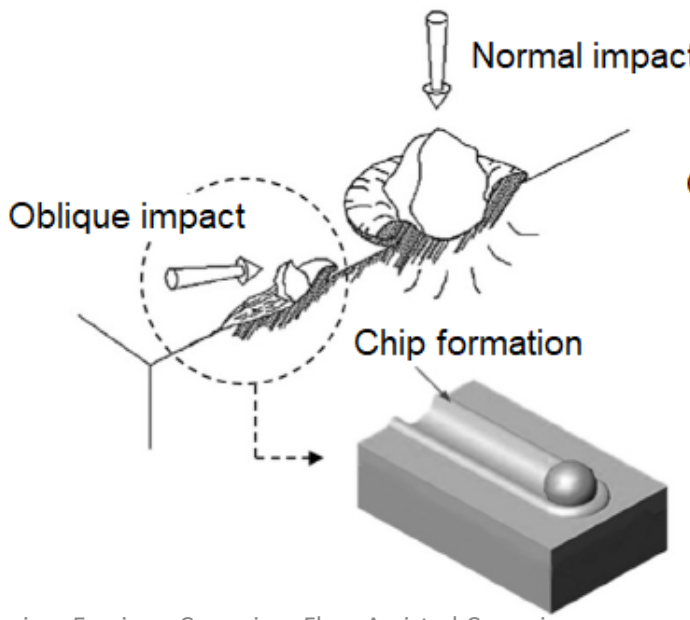
- Two components
  - Deformation erosion (E_D)
  - Cutting erosion (E_C)
    - Two types of cutting erosion (I & II)



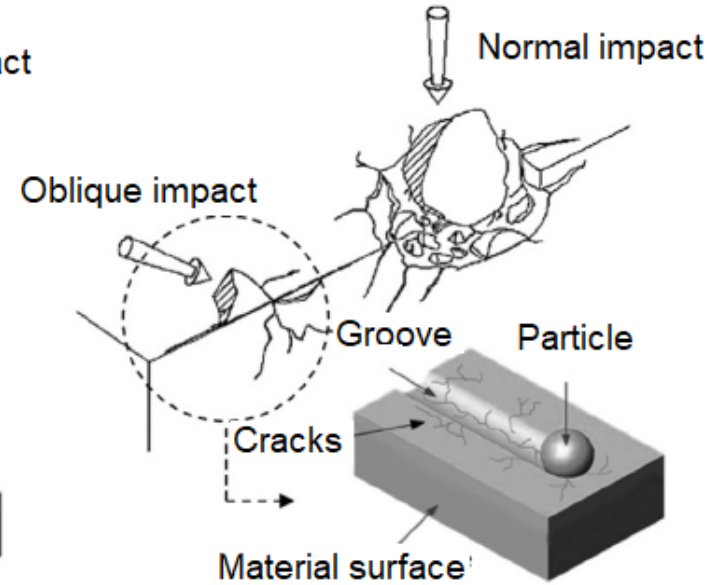
Turbulent flow



Laminar flow

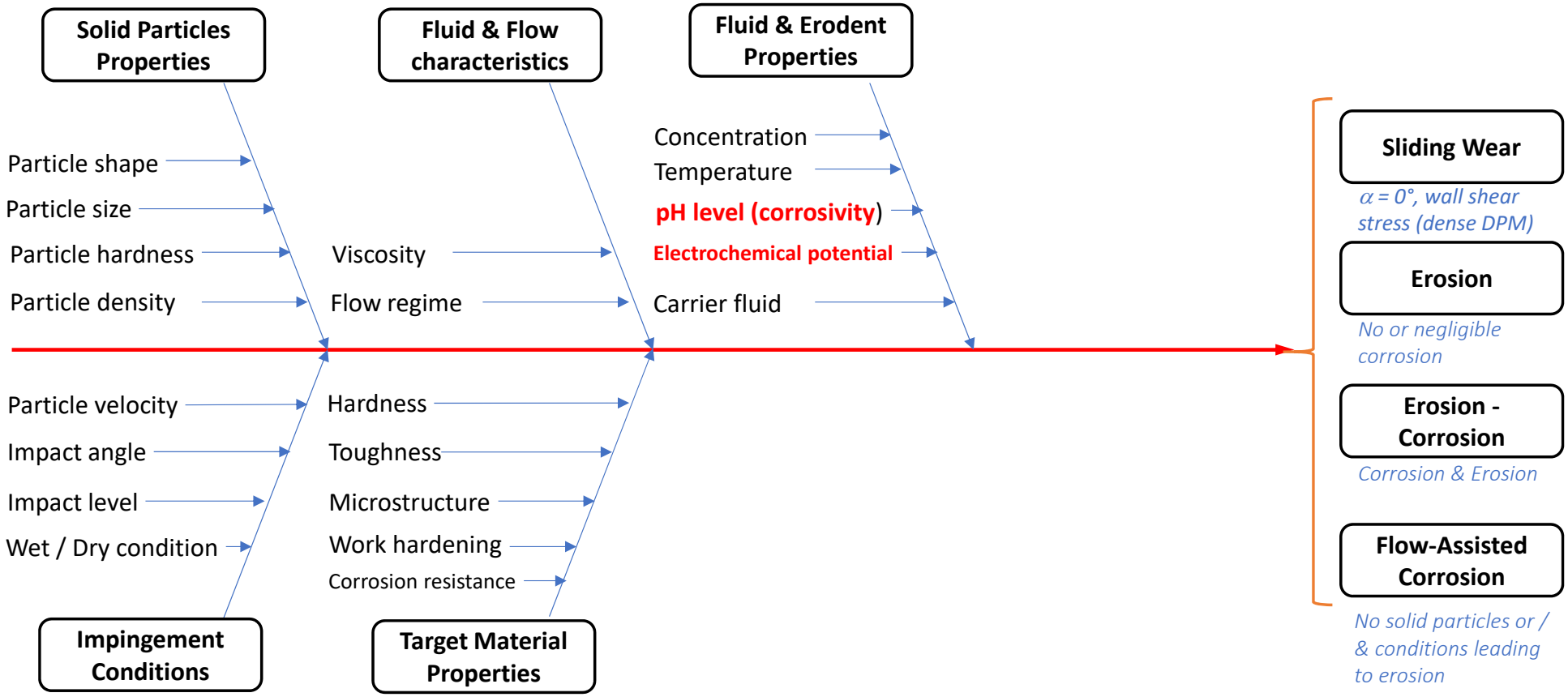


Erosion of ductile materials



Erosion of brittle materials

Important parameters for Erosion (Solid dilute or dense particle system)



Classification according solid particles concentration

- Dilute particle system
  - Concentration of erodent in carrier fluid low, very low level of particle – particle interaction
    - e.g.: Sand in carrier fluid < 500 ppmV
- Dense particle system
  - Concentration of erodent in carrier fluid important, particle – particle interactions are considered
  - Solid volume effect
  - Abrasive erosion: The wall shear stress effect shall be considered
    - e.g.: Slurries (1% up to 50% of solid fraction (volume))

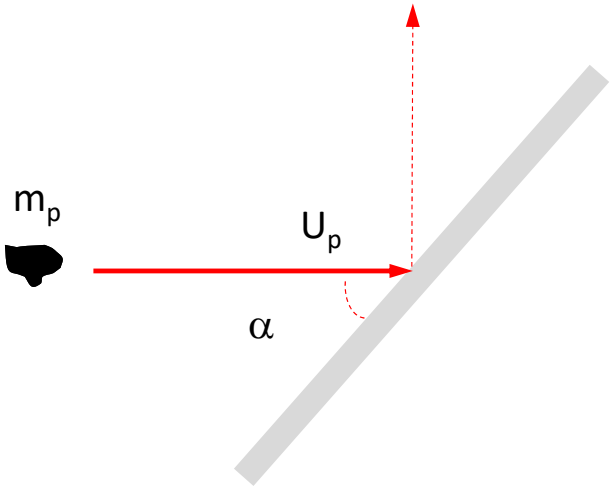
Expression of erosion & Current erosion models

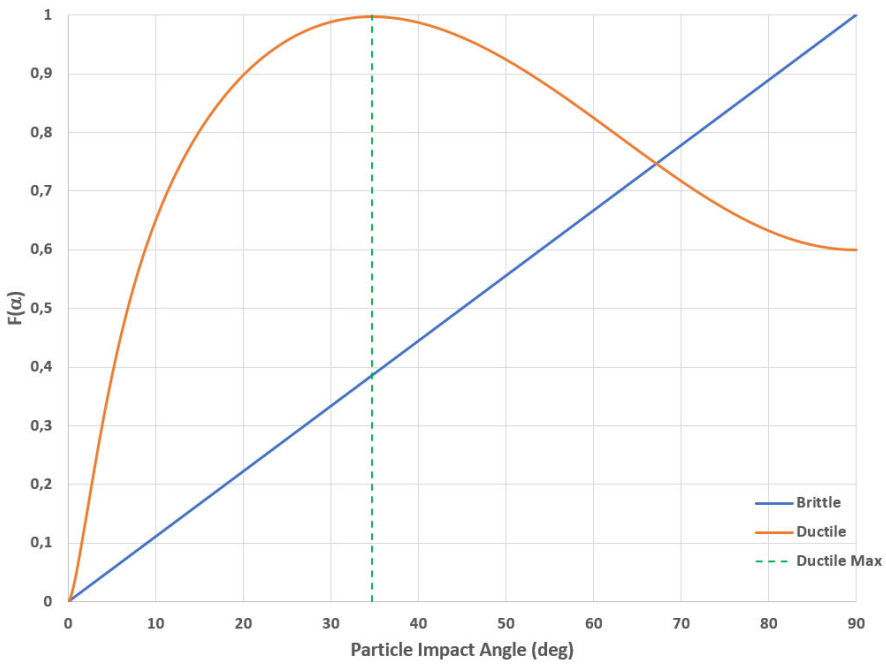
- Erosion ratio

$$\mathrm{ER} = \frac{\text{Mass of removed material}}{\text{Mass of erodent}}, \qquad \propto (\mathrm{V}, \theta, \mathrm{Hv}, \rho, \mathrm{D}, \mathrm{Fs})$$

- Erosion Models
  - Fluent Erosion model (*default model ANSYS*)
  - Mclaury, et. Al erosion model
  - Salama and Venkatesh erosion model
  - Finnie erosion model (from 1960, one of the first)
  - Oka erosion model
  - Zang (ECRC) erosion model
  - Grant and Tabakoff erosion model
  - DNV Erosion model, (based on Huser & Kvernvold work (2007))
  - Tulsa erosion model (*Oil & Gas, sand erosion*)

Erosion model, carbon steel (DNV-GL RP O501)





Material properties (K, n, F(α)) Actual material loss rate [kg/s]

$$E_m = K \cdot U_p^n \cdot F(\alpha) \cdot m_p$$

Ductile material

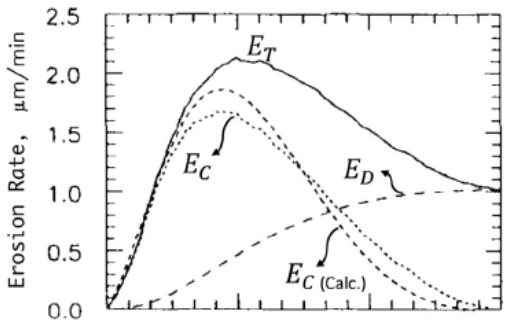
$$F(\alpha)_{ductile} = A \cdot \left[\mathrm{Sin}(\alpha) + B\left(\mathrm{Sin}(\alpha) - \mathrm{Sin}^2(\alpha)\right)\right]^k \cdot [1 - \exp(-C \cdot \alpha)]$$

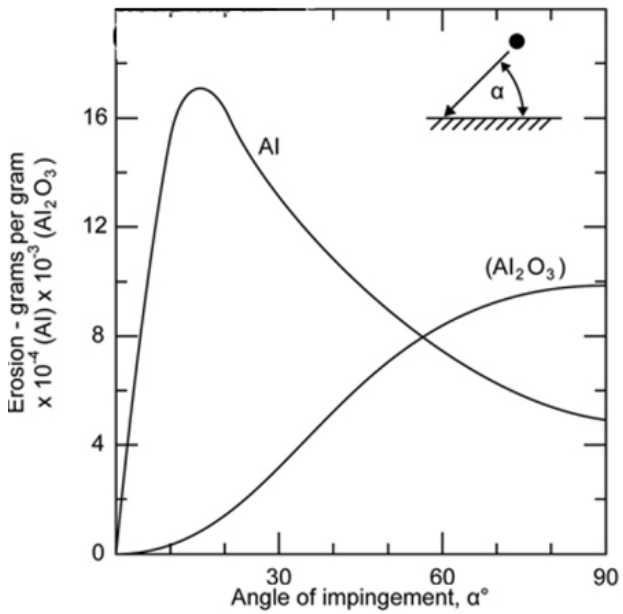
$F(\alpha) \in [0,1]$ for $\alpha \in \left[0, \frac{\pi}{2}\right]$ A = 0.6; B = 7.2; C = 20; k = 0.6 (carbon steel)

Brittle material

$$F(\alpha)_{brittle} = \frac{2 \cdot \alpha}{\pi}; \; F(\alpha) \in [0,1] \text{ for } \alpha \in \left[0, \frac{\pi}{2}\right]$$

Erosion Model (Clark & Wong)





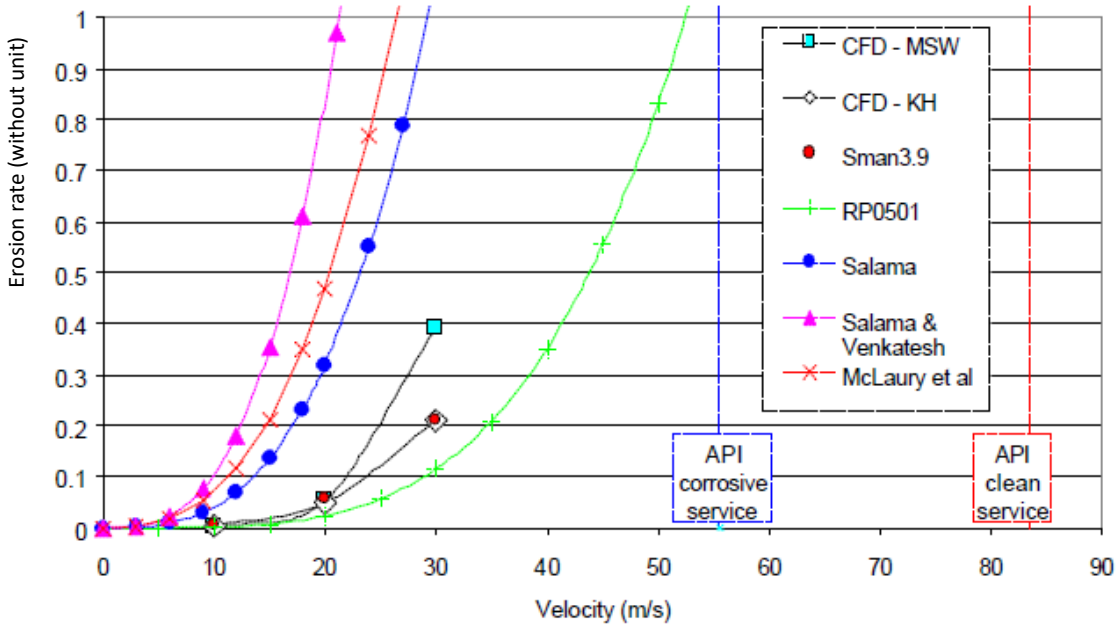
Total erosion (Clark & Wong simplified equations):

$$E_T = E_C + E_D$$

$$E_T = \frac{1/2 M_p (V_N^2)}{\varepsilon} + \frac{1/2 M_p (V_T^2 \sin 2\alpha)}{\varphi}$$

E_T: Total erosion
E_C: Cutting erosion
E_D: Deformation erosion
M_p: Total mass of uniformly sized particles
V_T: Tangential velocity
V_N: Normal velocity
α, ε, φ: Empirical constants (deformation erosion, cutting erosion)

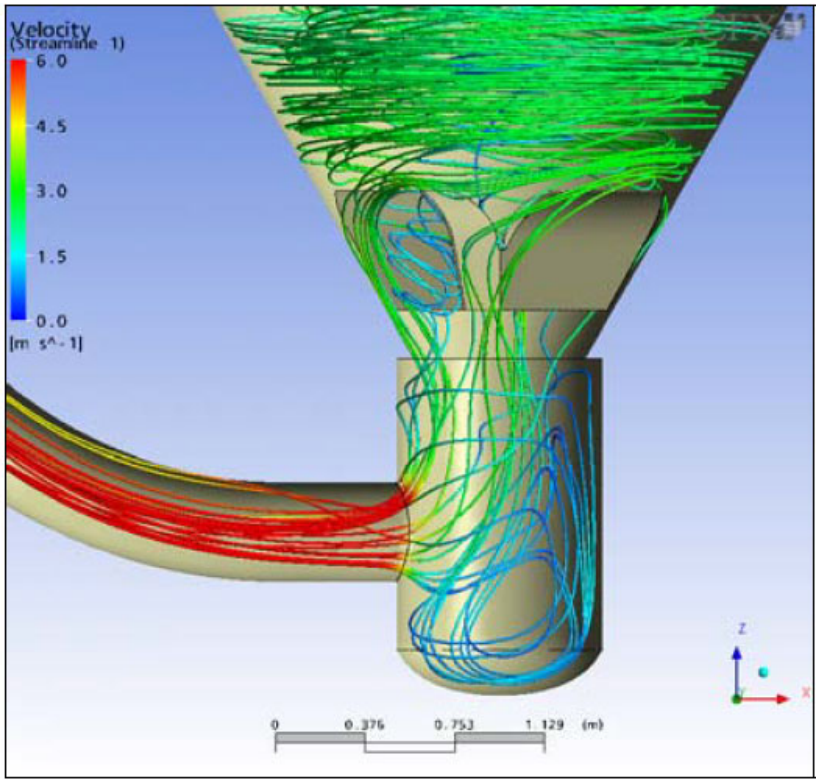
Erosion modeling, comparison of evaluation



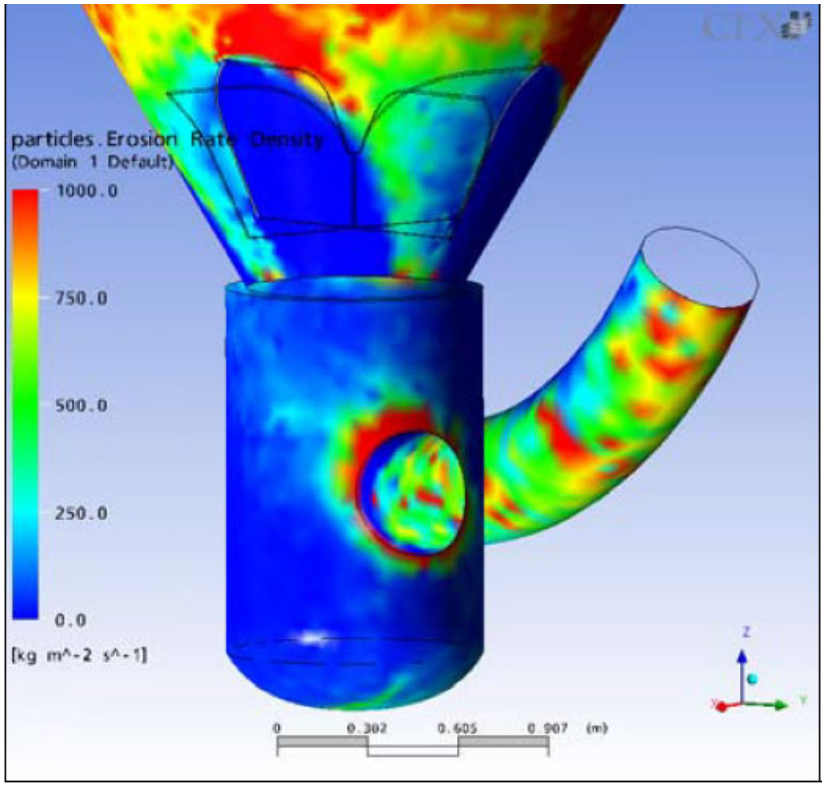
Erosion of a 2 inches elbow in CH_4 gas – Sand flow

Gas density: 4.82 kg/m^3
Gas viscosity: 1.1 * 10^{-5} Pas
Sand particle size: 150 µm
Sand density: 2650 kg/m^3
Elbow diameter: 55 mm
Elbow r/D: 1.5
Steel grade Brinell hardness: 210
Sand concentration: 21.6 ppmV

Erosion in a slurry transfer system (alumina)



Alumina Slurry System - Velocity profile

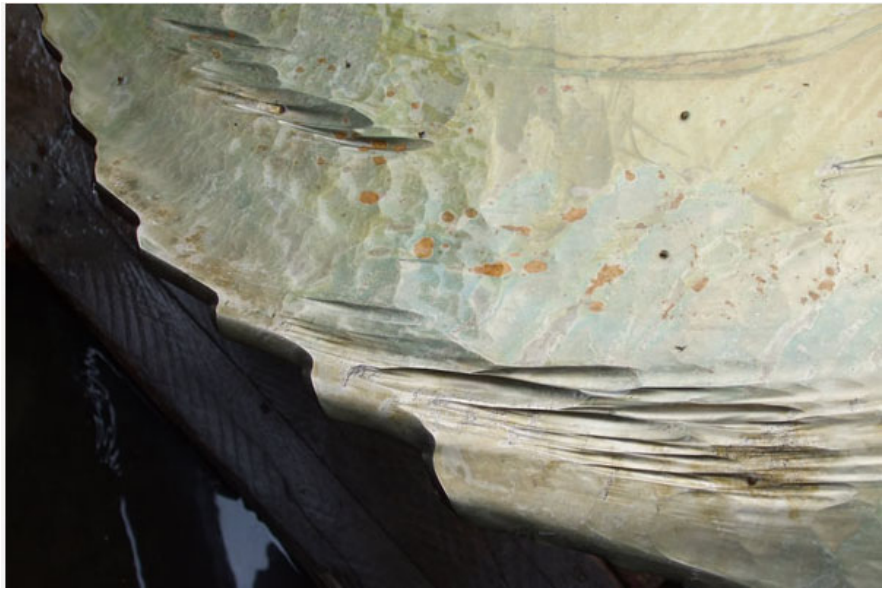


Alumina Slurry System – Erosion Profile

Gary Brown, 5th International Conference on CFD in the Process Industries, CSIRO, Melbourne, 13-15 Dec. 2006

Cavitation – erosion damage

Cavitation – erosion of blade edge



Severe cavitation – erosion of blade edge

Cavitation - erosion

Cavitation – erosion of a diesel cylinder

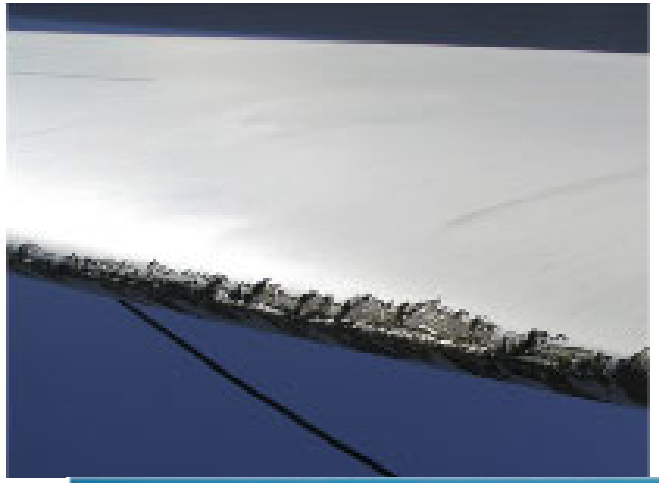
- Cavitation-erosion often found in diesel engines on the external walls of wet cylinder liners.
- The amount of erosion may vary from engine to engine and cylinder to cylinder
- Vertical strips or patches of damages corresponding with the piston thrust face.
- May be caused by excessive harmonic vibrations in the engine.

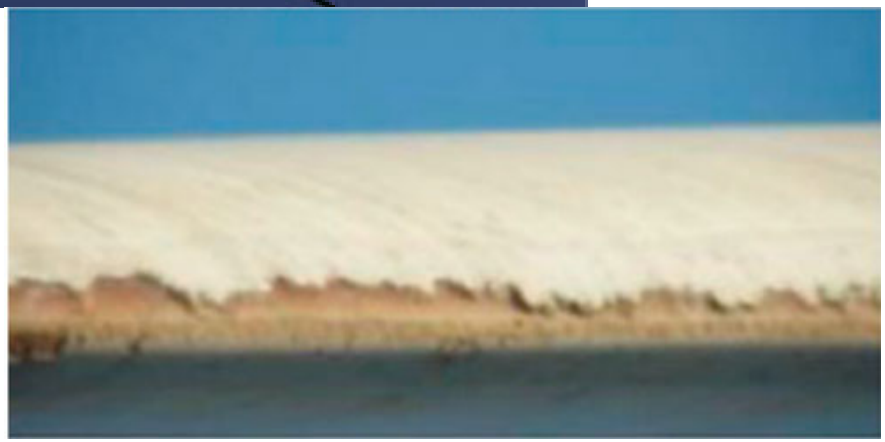
Cavitation – erosion of UT transducer

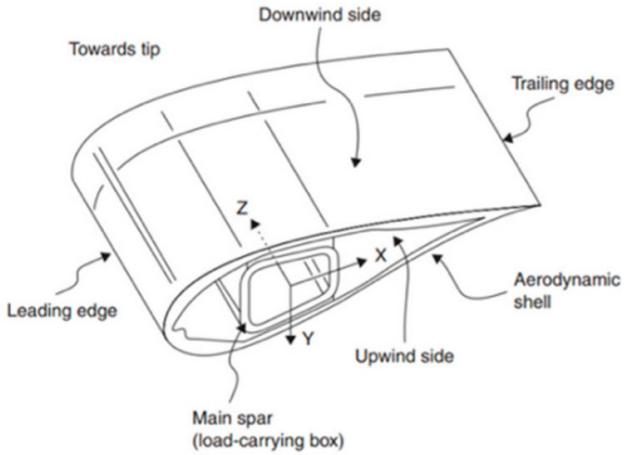
Cavitation – erosion of UT transducer (high vibrational energy)

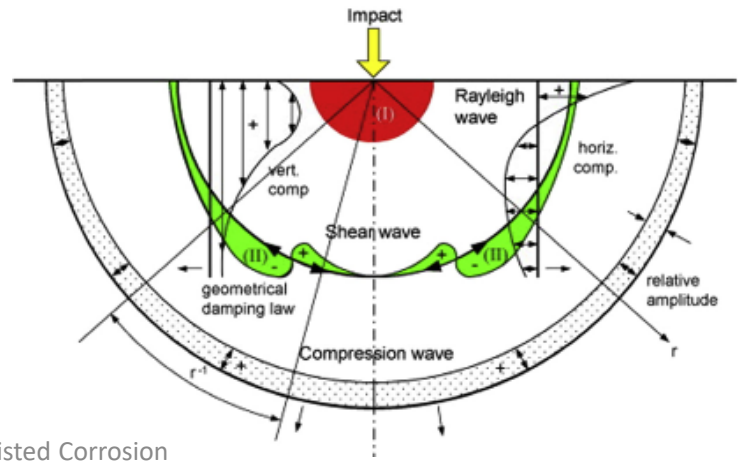
Surface cavitation-erosion: result of the forces created at the surface of the ultrasonic transducer as vibrational energy is transferred from the vibrating surface to the liquid in contact with it. Metal is removed from the transducer surface as cavitation bubbles implode in contact with it. Most severe for transducer operating at less than 100MHz

Leading edge erosion of wind turbine blades









EROSION - CORROSION

- Numerous industries involved such as:
  - Food industry, Automotive components, Fluidized bed combustors, Nuclear power plants, Mining, Extractive metallurgy, Chemical industry,
  - Hydroelectric power plant,
  - Marine pumping,
  - Sea water reverse osmosis desalination plants,
  - Oil & Gas industries.

EROSION - CORROSION

- Erosion– corrosion: complex interaction of erosion, (mechanical driven process), and corrosion, (electrochemical driven reaction) at the surface resulting in material loss.
- Both processes occur at the surface with their interaction being commonly referred to as synergy.
- Synergy: Difference between Erosion-Corrosion Rate and the sum of Erosion Rate alone and Corrosion Rate alone

$$S = V_{EC} - (V_{0C} + V_{0E}), \qquad S = \Delta V_C + \Delta V_E$$

Expression of synergy

- ΔV_C can be split in
  - ΔC_f: Effect of erodent damage of a passive film leading to corrosion of the underlaying surface
  - ΔC_e: Effect of erodent deforming the surface leading to increased corrosion activity
- ΔV_E can be split into 3 parameters
  - ΔE_p: enhancement of wear from corrosion between metallic phases
  - ΔE_m: influence of corrosion on the mechanical properties of the surface material
  - ΔE_s: Enhancement of wear by oxide layer formation
- Overall synergy:

$$S = \Delta C_f + \Delta C_e + \Delta E_p + \Delta E_m + \Delta E_s$$

Synergy for erosion enhanced corrosion

- Positive synergy
  - Local acidification in the erosion pits
  - Increased ionic transport by turbulence
  - Lowering of fatigue strength of the metal by corrosion
  - The removal of work hardened surface by corrosion process
  - Preferential corrosive attack at grain boundaries
  - Increased number of stress concentration defects resulting from corrosion micro pitting
- Negative synergy
  - Strain hardening (generally)
- Synergic effects depend of the metallic material and carrier fluid

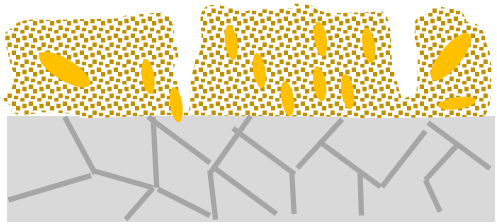
Synergy mechanisms

- Martensic steel in sea water
  - Spalling of exposed Cr_xC_y precipitated at grain boundaries (localized corrosion depleting Cr in the surrounding matrix)
  - Intergranular corrosion followed by mechanical removal of the metal matrix close grain boundaries
  - Corrosion of metallic matrix followed by mechanical removal of corrosion products
- Other alloys
  - Depending of alloy and fluid chemical & physical properties

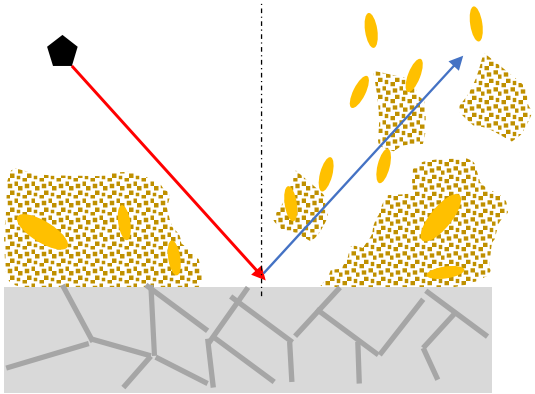
Evaluation of Erosion rate and corrosion rate

- Corrosion rate in dissolution regime: Application of Faraday's Law
- Corrosion rate in the passive region:
  - Several methods, based on evaluation of energy involved in the erosion process (difference between the initial and rebound impact energy and that the erosion process is adiabatic), the steps of the evaluation could be:
    - Evaluation of energy balance
    - Evaluation of crater diameter and crater depth
    - Evaluation of the passive film removed per impact
    - Evaluation of particle impact frequency
    - Evaluation of the thickness of passive layer
- ASTM G119-09(2016): Standard Guide for Determining Synergism Between Wear and Corrosion

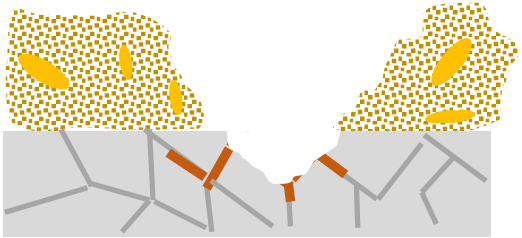
Erosion – Corrosion steps



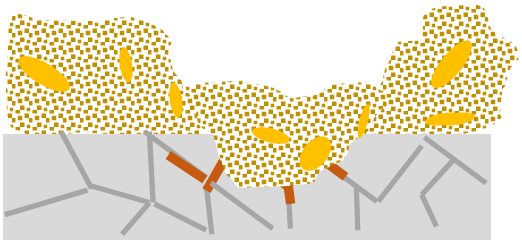
Metal & passivation layer



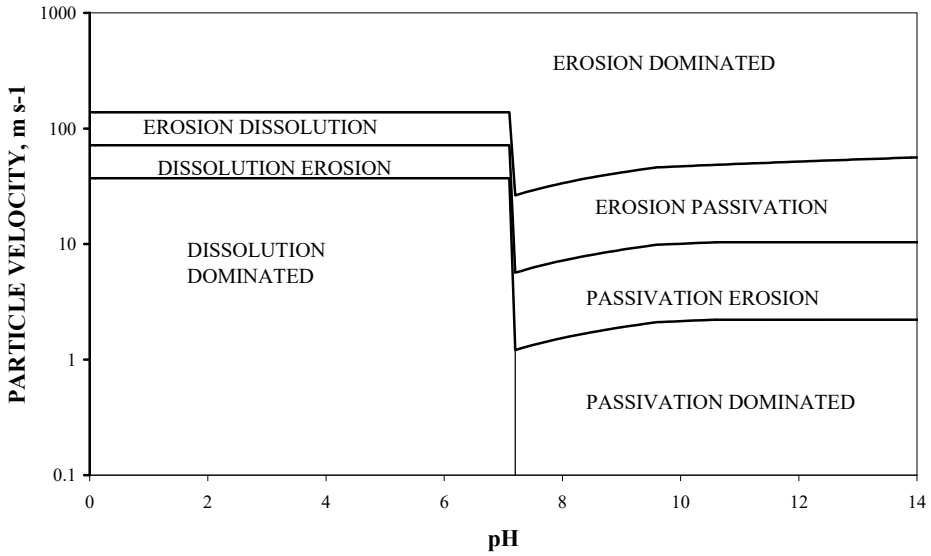
Impingement erosion of passivation layer



Localized corrosion at grain boundaries, formation of pit & corrosion



Erosion – Corrosion Maps



Particle velocity pH maps for iron at –0.45V/SCE

$$\frac{V_C}{V_E} = \frac{V_{C0} + \Delta V_C}{V_{E0} + \Delta V_E},$$

$V_C + V_E = V_{EC}$

Regime maps

Erosion dominated: $V_C/V_E < 0.1$

Erosion – dissolution: $0.1 \leq V_C/V_E < 1.0$

Dissolution – Erosion: $1.0 \leq V_C/V_E < 10.0$

Dissolution dominated: $V_C/V_E \geq 10.0$

Wastage maps

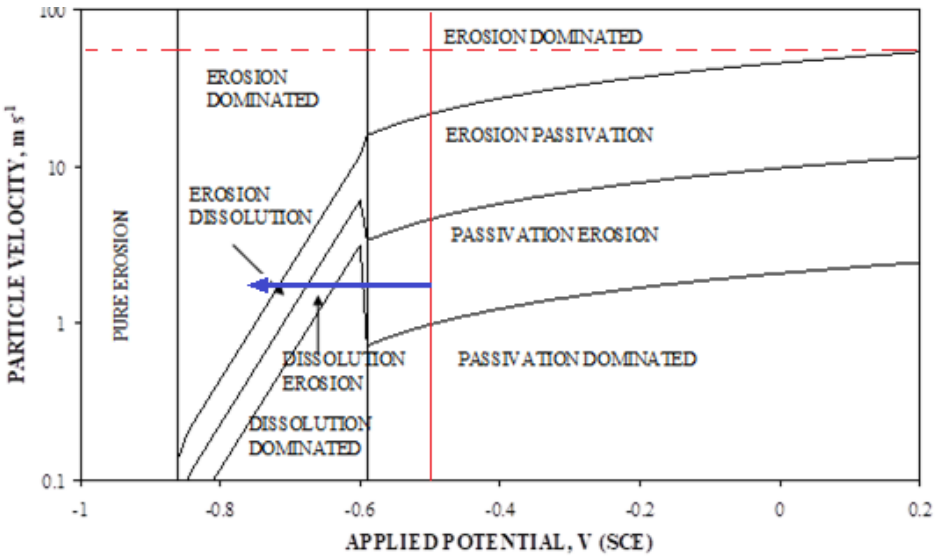
Low: $V_{EC} < 1.0$

Medium: $1.0 \leq V_{EC} < 10.0$

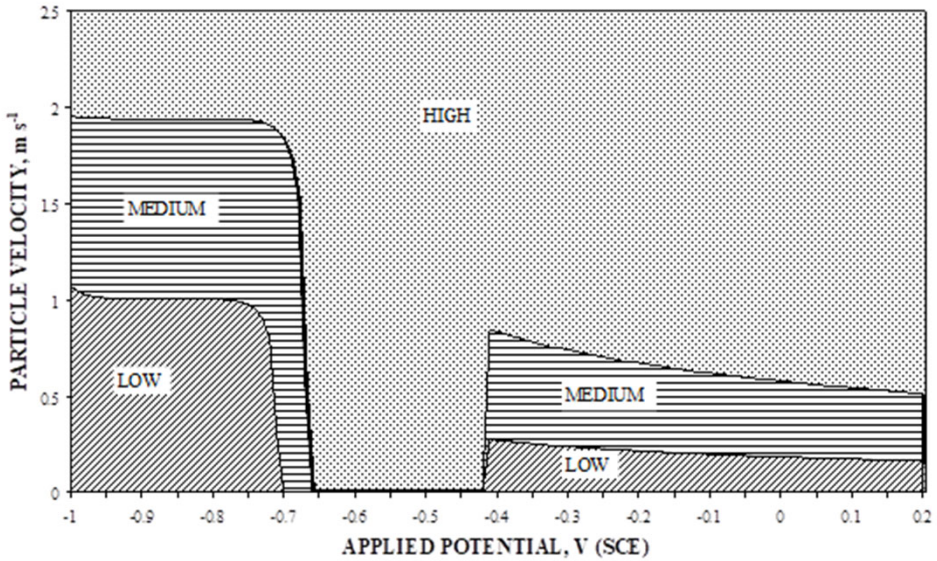
High: $V_{EC} \geq 10.0$

Margaret Stack et. al

Erosion – Corrosion Maps



Particle velocity-applied potential regime maps of iron at pH 7 for normal erosion impact



Particle velocity-applied potential wastage maps of iron at pH 7 for normal erosion impact

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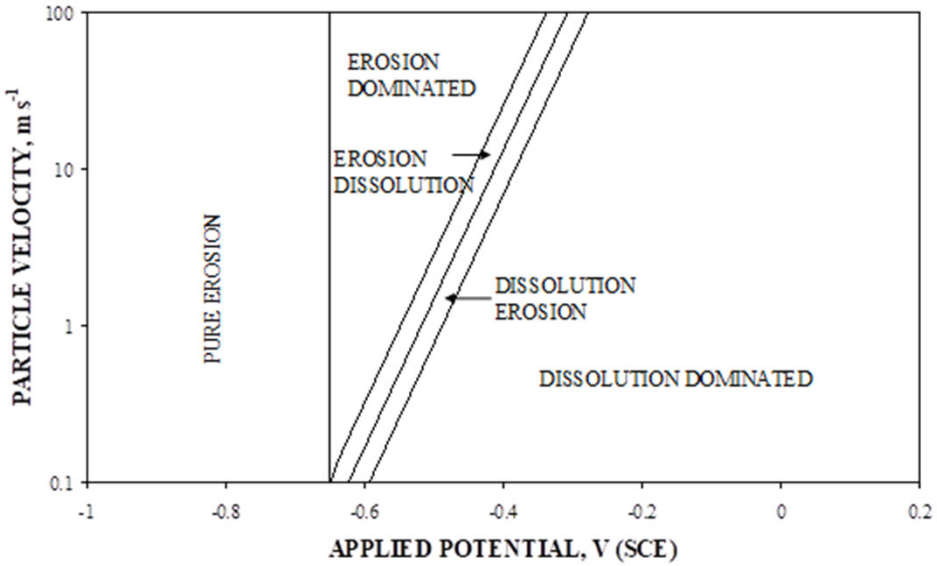
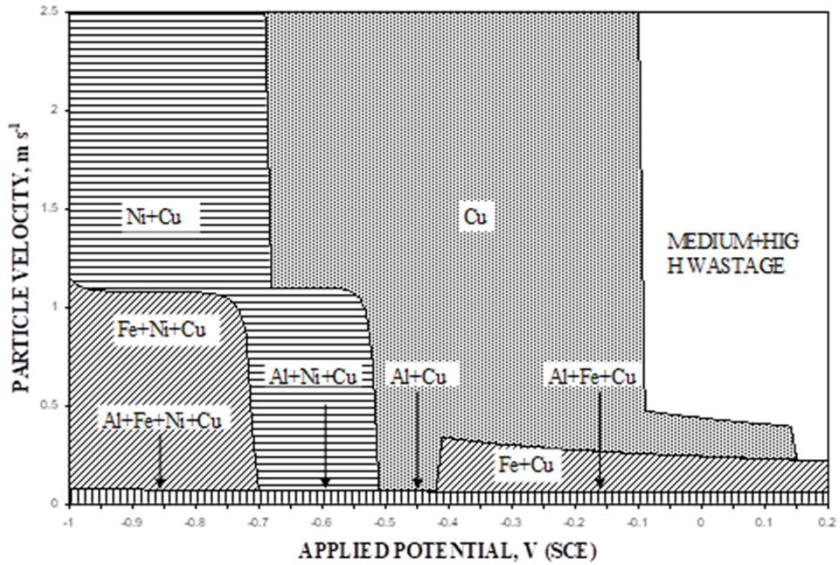
Erosion – Corrosion Maps



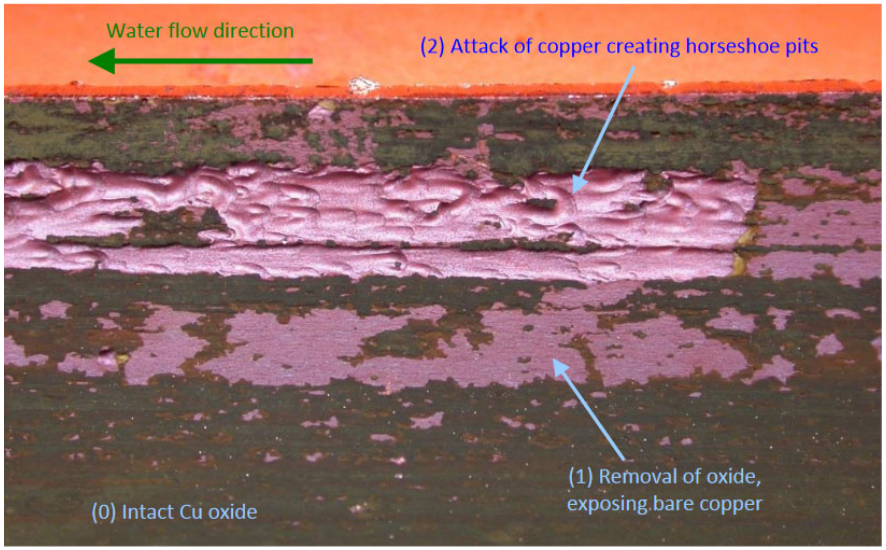
Particle velocity–applied potential maps for Cu at pH 5



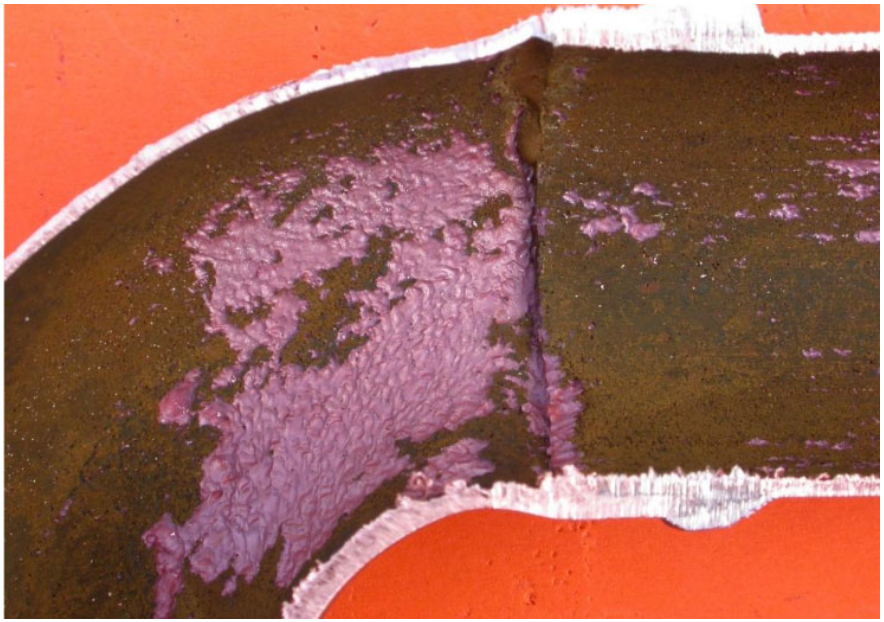
Materials performance maps based wastage maps of Fe, Cu, Ni, and Al, showing where low wastage is observed for the various pure metals at pH 7 for normal erosion impact

Margaret Stack et. al

Erosion – Corrosion of copper in hot water

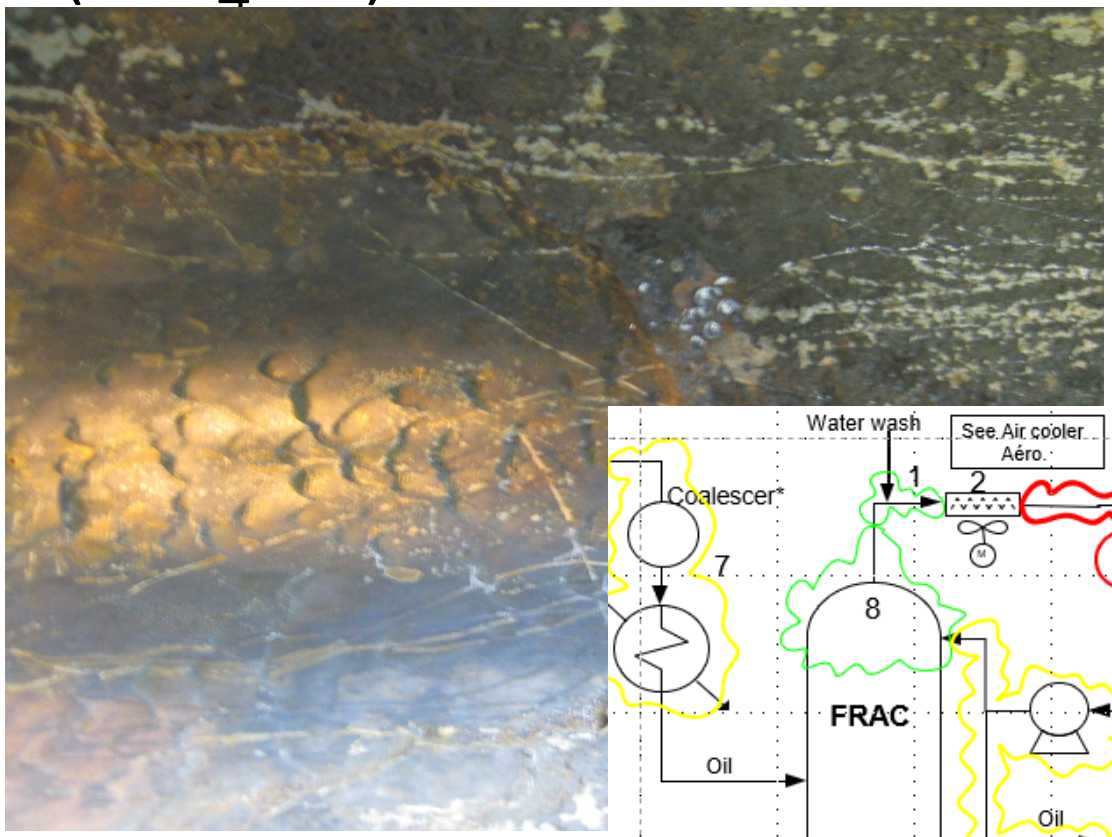


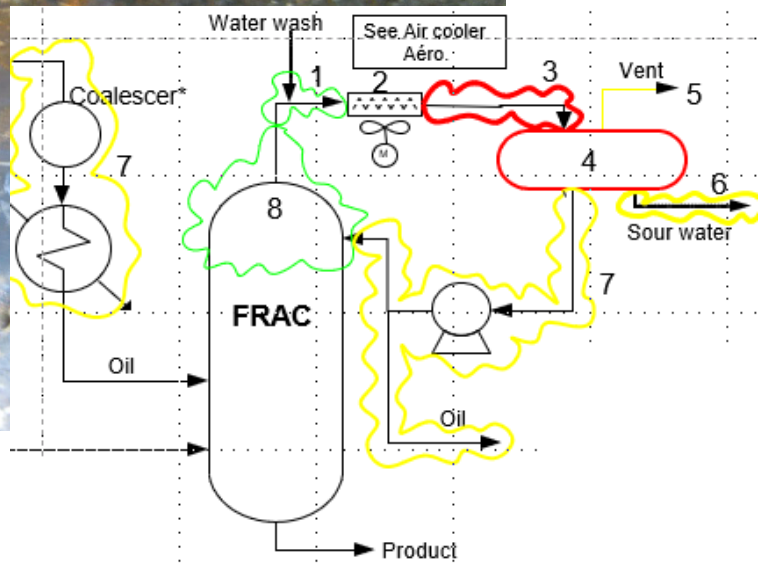
Corrosion and Erosion – Corrosion of copper showing horseshoe attack



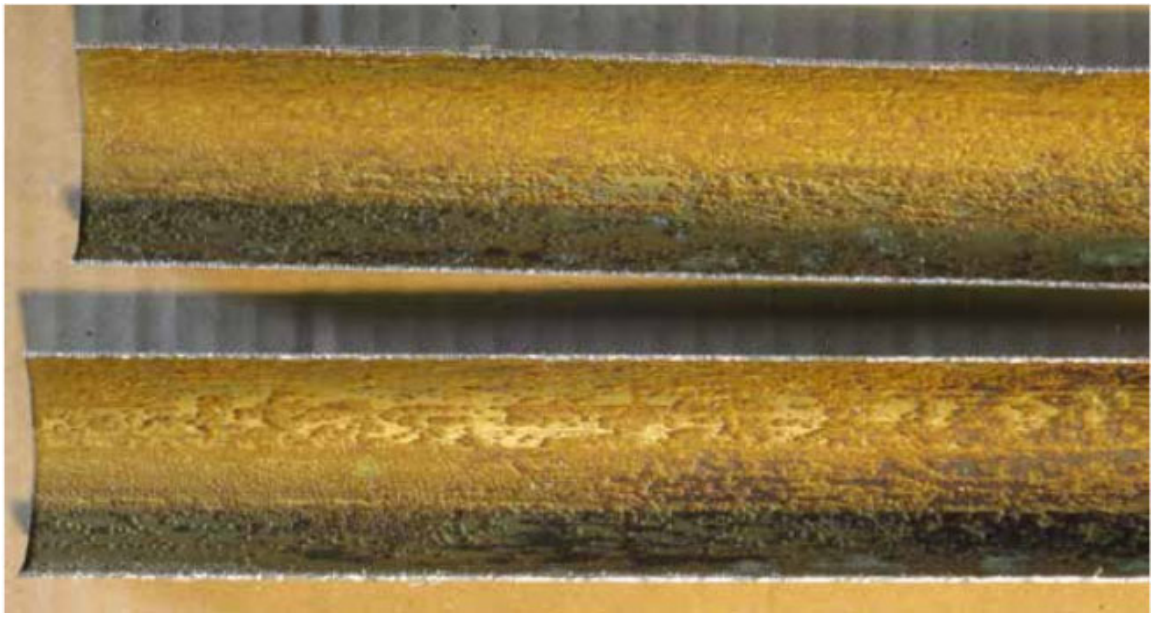
Erosion-Corrosion downstream of a joint, apparently due to turbulence at the joint

Erosion-corrosion (NH_4HS)

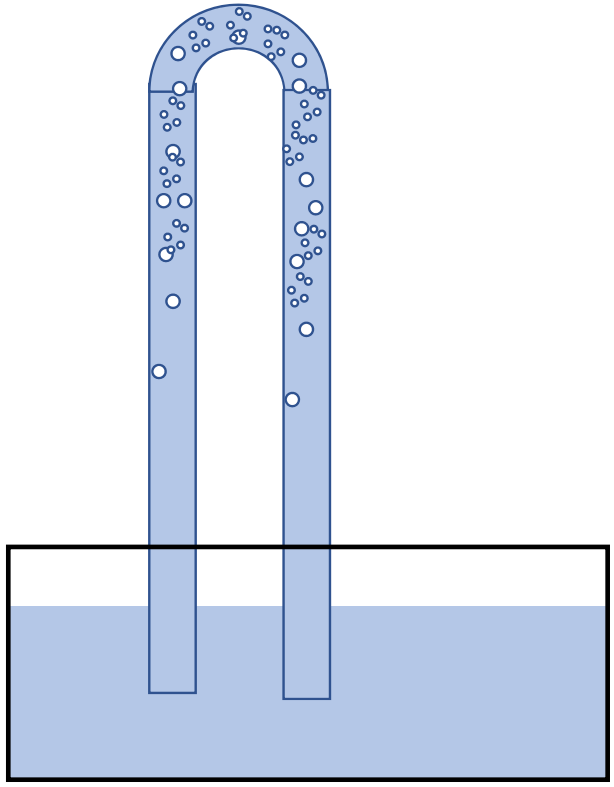




Erosion – Corrosion of Copper-Nickel alloy



Erosion-Corrosion of 25.4 mm OD 66/30/2 Cu Ni-Fe-Mn alloy in a dump condenser due to syphonic air release



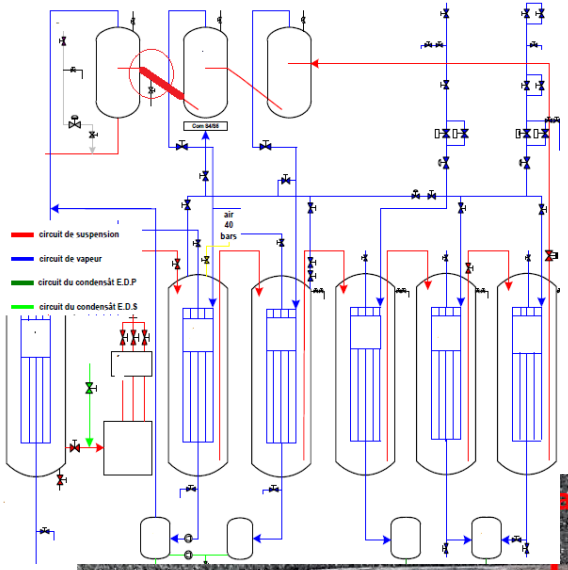
Copper alloys in seawater: avoidance of corrosion

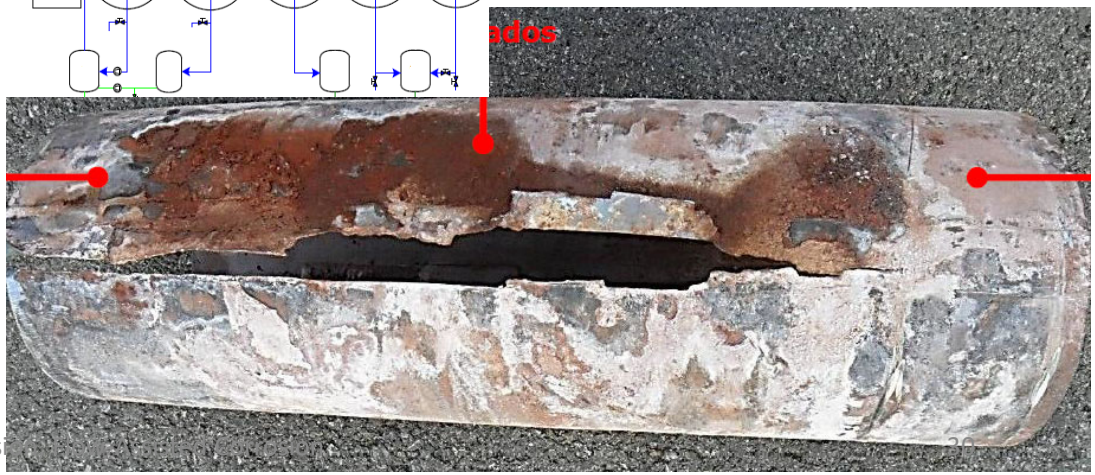
Erosion – Corrosion (impingement) of reformer furnace elbow

U-bend showing impingement hole on the outer radius

Close-up the hole reveals a thick lipped rupture and no elongation or creep

Erosion – Corrosion of Mild steel in hot caustic – alumina separators transfer lines





FLOW-ASSISTED CORROSION

- Numerous corrosion mechanisms are or may be flow-assisted
  - All mechanisms related to mass transport (mass transport is related to flow regime)
    - Naphthenic acid corrosion,
    - Dissolution of passive layer in boiler feed water, condensates, and saturated steam circuits (steam power generation),
    - Lead-bismuth eutectic,
- Flow-assisted corrosion involve flow-dependent corrosion mechanisms.
- Flow-assisted corrosion doesn't involve erosion, but erosive conditions may be present in the same flowing stream
- Some forms of flow-assisted corrosion seem to be shear-stress dependent, it is not general and not totally demonstrated.

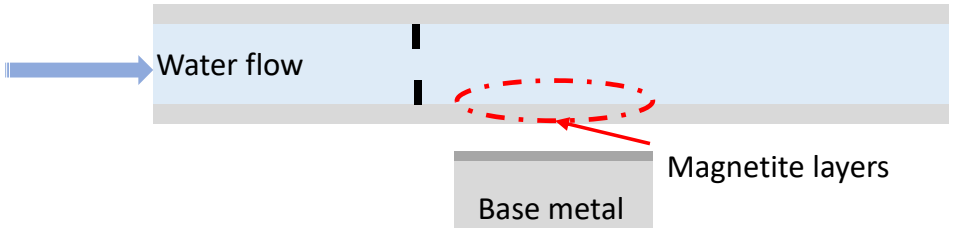
Flow-Assisted Thinning

Destruction of ID Protective Oxide Layer

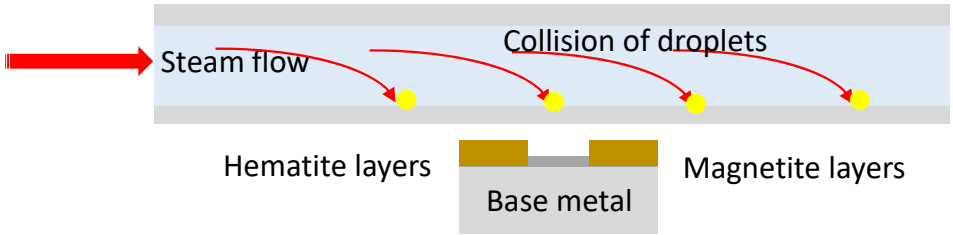
FAC → Chemical dissolution

Erosion →

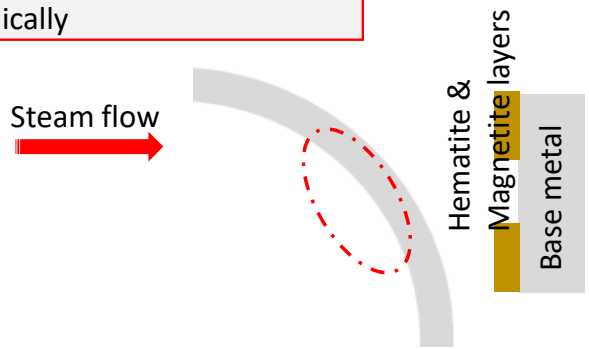
Cavitation Erosion Flashing Erosion Droplet Impingement Erosion Solid Particle Erosion	Cavitation process (static Pressure < Vapor Pressure) Like Erosion-Cavitation w/o Bubble Collapse Two-Phase Flow Conditions / Large Pressure Drop Mechanically



FAC due to increasing mass transfer (flow regime)
Mitigated by flow chemistry control

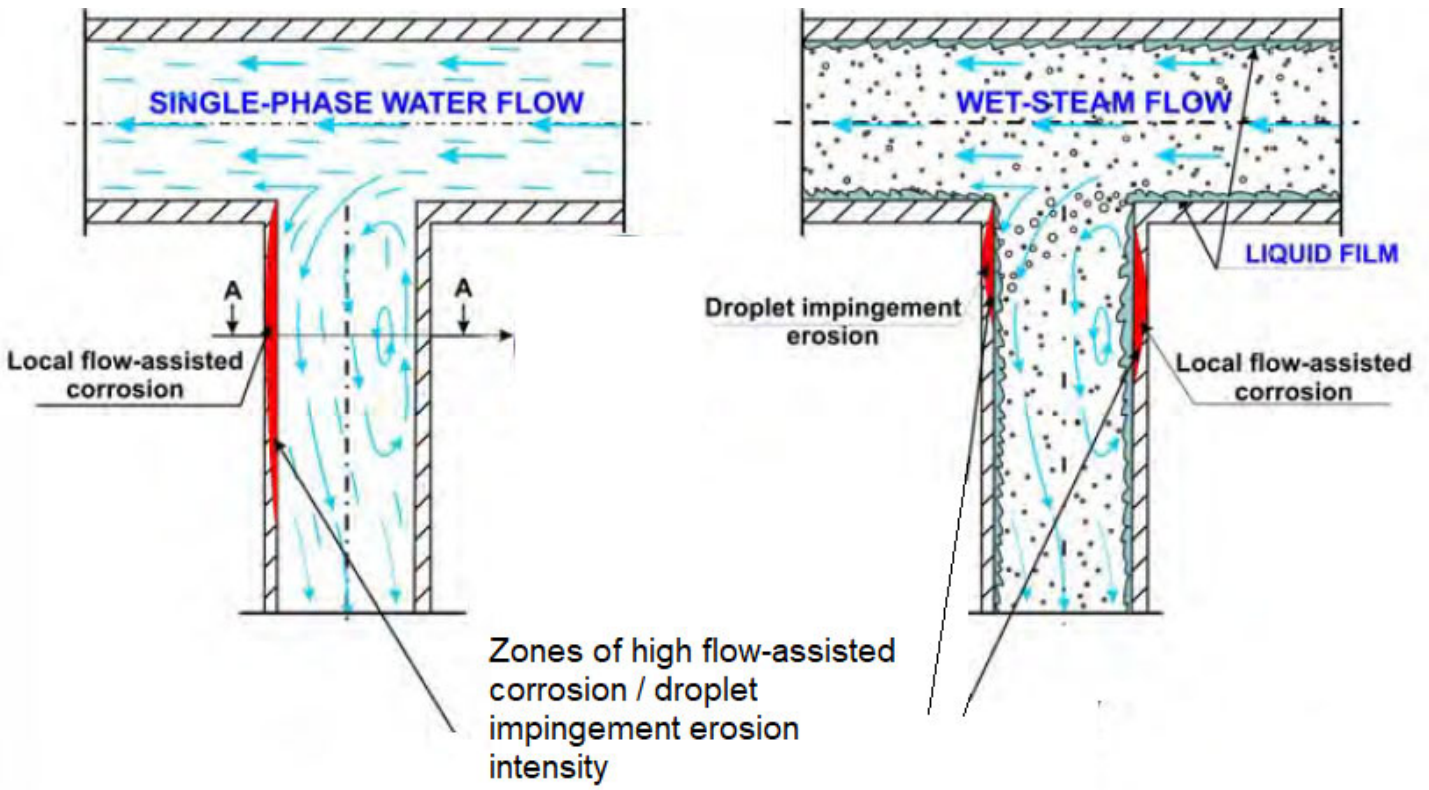


Erosion-corrosion (tiger strip pattern)
Due to collision of droplets at nodes of standing sonic wave of steam flow
Mitigated by metallurgy [Cr]>0.2%



LDI (shot-gun pattern), due to liquid droplet collision at bend

Coexistence of FAC and Liquid Droplet Impingement Erosion



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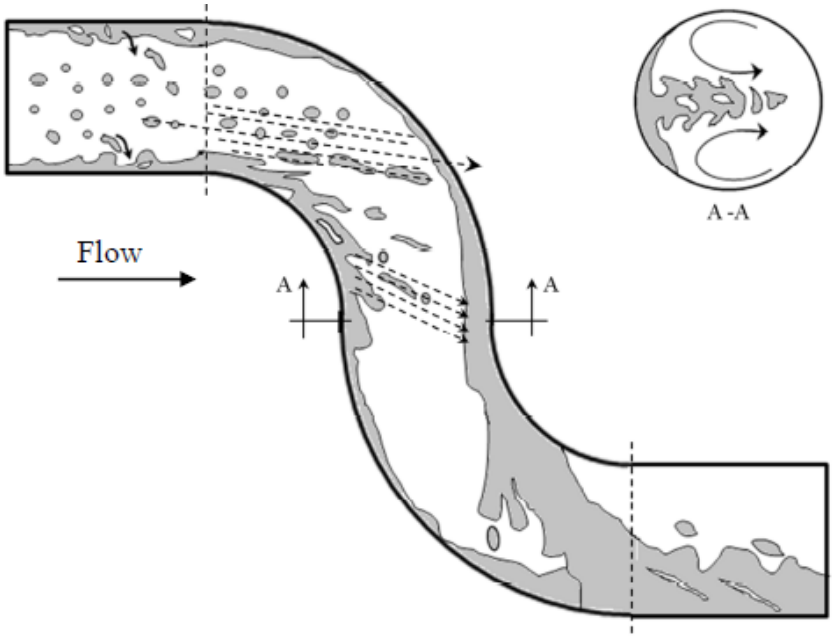
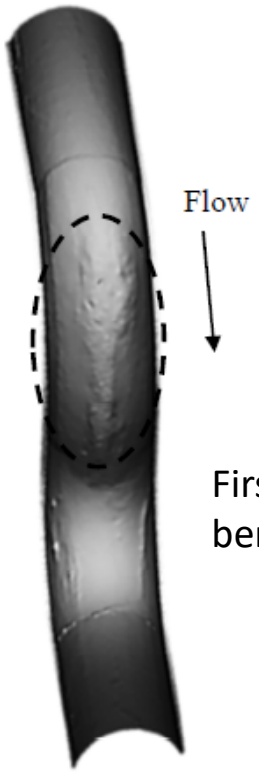
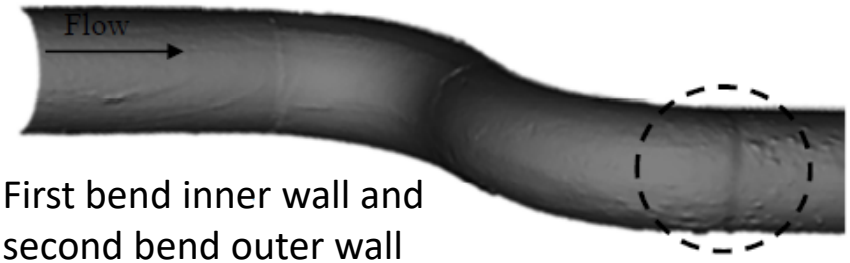
Phases redistribution





First bend outer wall and second bend inner wall

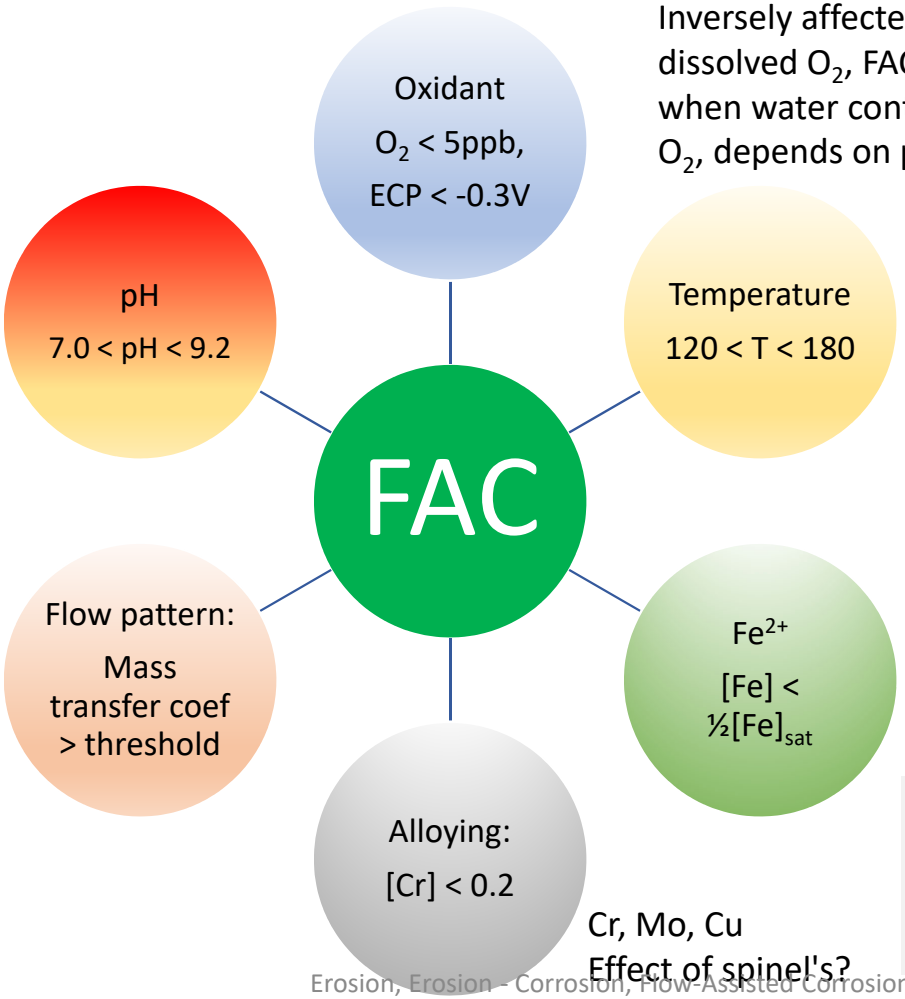


First bend inner wall and second bend outer wall

FAC in BFW, condensates water, & saturated steam

Inversely affected by amount of dissolved O_2, FAC rate strongly decrease when water contains more than 20 ppb O_2, depends on pH, contaminants.

FAC wear rate increases in the range pH 7.0 – 9.0, drops sharply above pH 9.2,
Critical parameter pH of liquid phase



Single phase flow: 80 < T < 230°C
Two phases flow: 140 < T < 260°C,
Location of max wear rate changes with pH, O_2 and other variables
Wear rate highest at 150°C / increases with velocity

Flow rate have a linear effect on the FAC wear rate

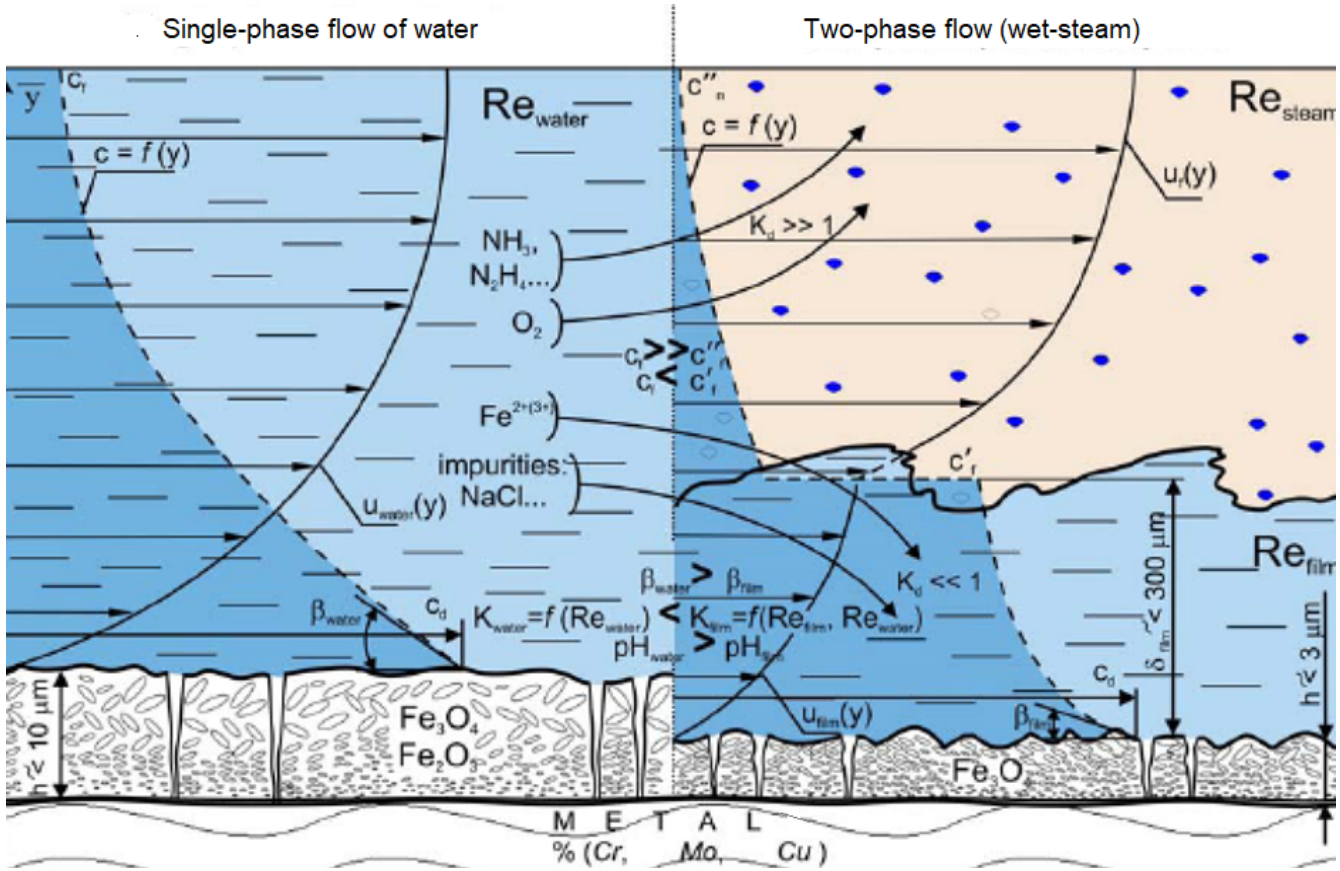
Cr, Mo, Cu
Effect of spinel's?

Entrance effect: This effect occurs when flow passes from a FAC-resistant material to a non-resistant material, which causes a local increase in the corrosion rate.

FAC wear rate evaluation

- Several models
  - Sanchez-Caldera
  - Mecano electro chemical model, Lu and Luo
  - EPRI: CHECWORKS
  - EDF: BRT CICERO
  - KWU - WATHEC
  - AREVA - COMSY
  - RAMEK
  - ECI

Local chemistry vs phase flow



Single phase water flow: Parameters determining the nature and intensity of corrosion factor (pH, Conductivity, O_2, Fe^{2+}, Alkalization additives, Impurities, …) slightly change over section and along channel: Bulk chemistry may be used

Two-phase flow: The mechanism of FAC is determined by local values of the physico-chemical parameters in the liquid film and in the two-phase layer close to the wall

The local pH of the liquid film may differ strongly of the bulk pH of the flow.

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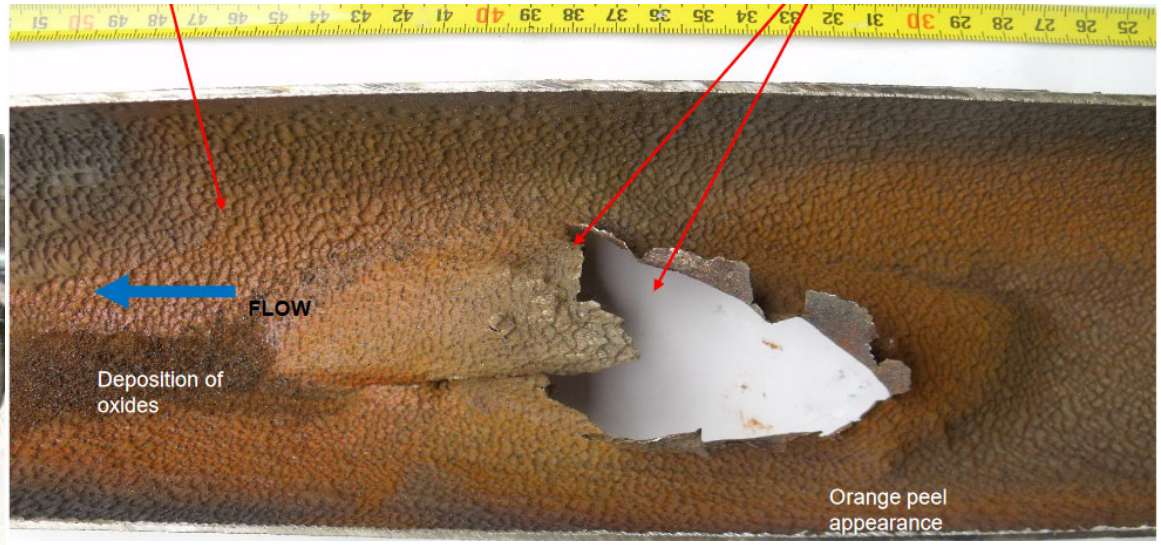
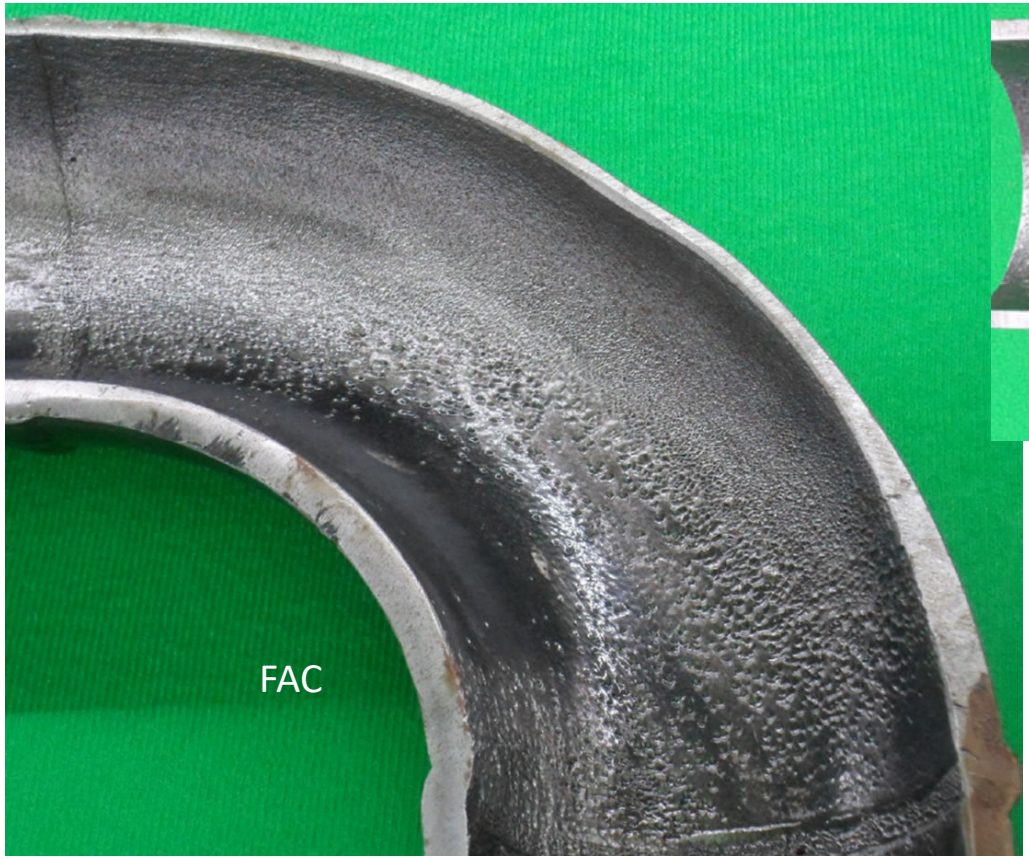
Example of Flow-Assisted Corrosion

MIHAMA 3 Condensate pipe rupture



Single phase FAC rupture failure

Comparison of FAC & LDIE



FAC (steam coming from feed water) and
Liquid Droplet Impingement Erosion in a vent line

Mitigation

Erosion

- **Design**: Efficient, corrosion modeling allow to optimize design
- **Surface treatment & Coatings**: Can be efficient
- **Action on flow regime**: efficient in some case (e.g. design of pressure let down valves)
- **Cathodic Protection**: not significant effect
- **Inhibition**: Drag reducing additives in case of flow-induced erosion

Erosion – Corrosion / LAS

- **Design**: Positive effect, as for erosion
- **Surface treatment & Coatings**: can be efficient, as for erosion
- **Cathodic Protection**: positive effect, the protection potential is sometime lower that requested for corrosion alone
- **Inhibition**: efficient, depending of corrosion mechanisms, inhibitors active for corrosion alone are generally also active for erosion corrosion, use of high-shear resistance inhibitors is sometime advised

Monitoring

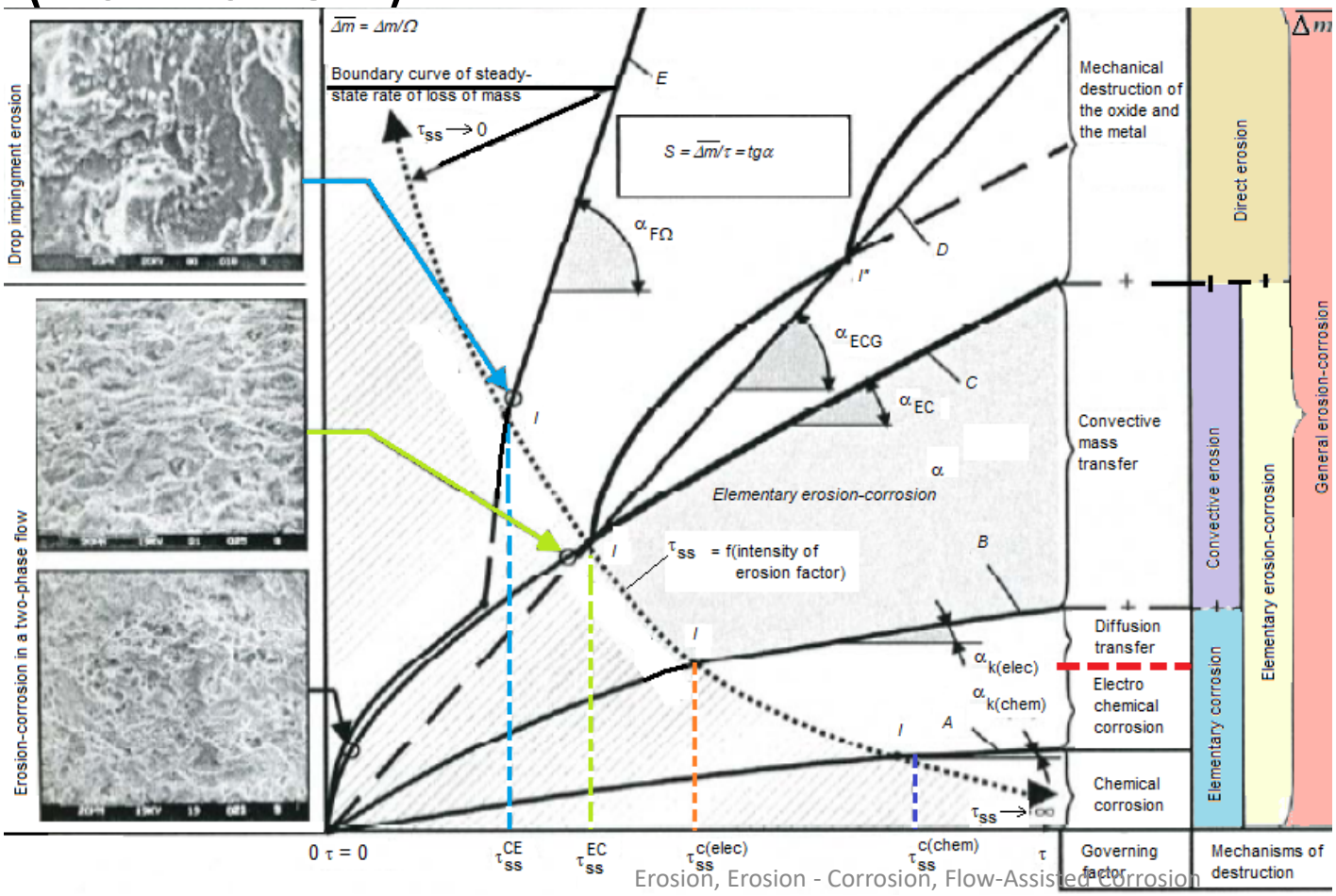
- Corrosion; Erosion probes
  - Electrical resistant probes,
  - Coupons
  - Sand probes
- Acoustic emission

Inspection

- Visual, Visual assisted: when accessible,
- X-Rays, γ-Rays
- Eddy-currents: exchangers tubes, small bores
- UT based methods
  - UT direct measurements (spot measurements)
  - IRIS (exchangers tubes)
  - UT Scan, UT phased array, Remote UT Scan: The most effective
- Analysis of results
  - Statistical methods (e.g. ANOVA, Weibull, Extreme values)

Back-up Slides & References

Mechanisms of destruction relationship (Tamarov)



In specific water chemistry conditions, the mechanisms of metal thinning are proposed to differ mostly by the nature of:

- *Erosive constituent, i.e. hydrodynamic factors*.

To illustrate that, kinetic curves of main degradation mechanisms.

- *corrosion in a laminar flow,*
- *erosion-corrosion with a convective mass transfer type,*
- *erosion with dominating mechanical metal degradation*.

Definitions

- Corrosion: The deterioration of a material, usually a metal, that results from a chemical or electro-chemical reaction with its environment
- Erosion: Progressive loss of material from a solid surface resulting from mechanical interaction between that surface and a fluid, a multicomponent fluid, or solid particles carried with the fluid.
  - Shear stress erosion: The surface of a material gets destroyed in single phase flow at high velocity, by the effect of shear stresses and the variations in the fluid velocity,
  - Droplet erosion (*Liquid Impact induced erosion*): occurs in two-phase flow by the impingement of liquid droplets entrained in flowing gases or vapors on surface metal,
  - Flashing-induced erosion: occurs when spontaneous vapor formation takes place due to sudden pressure changes,
  - Cavitation erosion: is caused by repeated growth and collapse of bubbles in a flowing fluid as a result of local pressure fluctuations.

Definitions

- Erosion-corrosion: Conjoint action involving erosion and corrosion in the presence of a moving corrosive fluid or a material moving through the fluid, leading to accelerated loss of material
  - Impingement Attack: is a form of corrosion of metals caused by erosion of the oxide layer by a moving fluid in which there are suspended particles or air bubbles
- Flow Assisted Corrosion: is a electrochemical corrosion process enhanced by chemical dissolution and mass transfer

Erosion models, API 14-E

- Notion of Erosional Velocity
  - Velocity above which erosion may occur can be determined by the following empirical equation

$$Ve = \frac{c}{\sqrt{\rho m}}$$

  - Ve: Fluid erosional velocity (feet/second)
  - c: empirical constant
  - ρm: gas/liquid mixture density at flowing pressure and temperature, lbs/ft^3
    - c = 100, continuous service; c = 125 for intermittent service (conservative values)
    - For solids-free fluids when corrosion is not anticipated, c = 150 to 200

Erosion-corrosion [HOLD]

Computational fluid dynamics models

- CFD modeling provide detailed information on the exact location and magnitude of the erosive wear

- Single phase computational fluid dynamics simulations
  - Applicable for dilute particle phase
  - Based on Eulerian-Langrangian methodology (to see also Summerfeld Lecture)
    - Single phase simulation + DPM (Discrete Particle Method)
  - Many supported erosion models
  - Potential to allow design to be optimized prior to testing

- Multiphase CFD simulations
  - More realistic for full particle loading from low, medium to high range
  - Based on Eulerian-Granular multi-fluid approach (to see ANSYS full, tutorial 23 ANSYS)
  - Capture four-way couplings including fluid-particle, particle-fluid, particle-particle, and turbulence interactions
  - Capture particle shielding and liquid damping effects

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