EROSION CORROSION ("Flow-Assisted" Corrosion)

An increase in corrosion brought about by a high relative velocity between the corrosive environment and the surface.

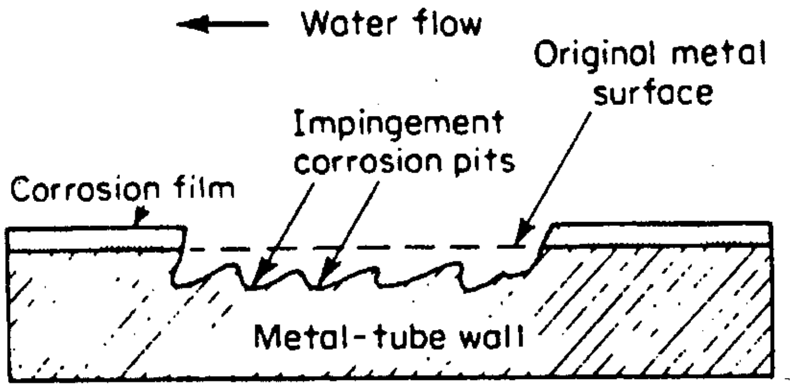
Removal of the metal may be:

- **as corrosion product which "spalls off" the surface because of the high fluid shear and bares the metal beneath;**
- **as metal ions, which are swept away by the fluid flow before they can deposit as corrosion product.**

N.B. Remember the distinction between erosion-corrosion and erosion:

- **erosion is the straightforward wearing away by the mechanical abrasion caused by suspended particles . . . e.g., sand-blasting, erosion of turbine blades by droplets . . .**
- **erosion-corrosion also involves a corrosive environment . . . the metal undergoes a chemical reaction.**

Erosion-corrosion produces a distinctive surface finish:
grooves, waves, gullies, holes, etc., all oriented with respect to the fluid flow pattern . . .



Erosion corrosion of condenser tube wall.

Erosion of stainless alloy pump impeller.

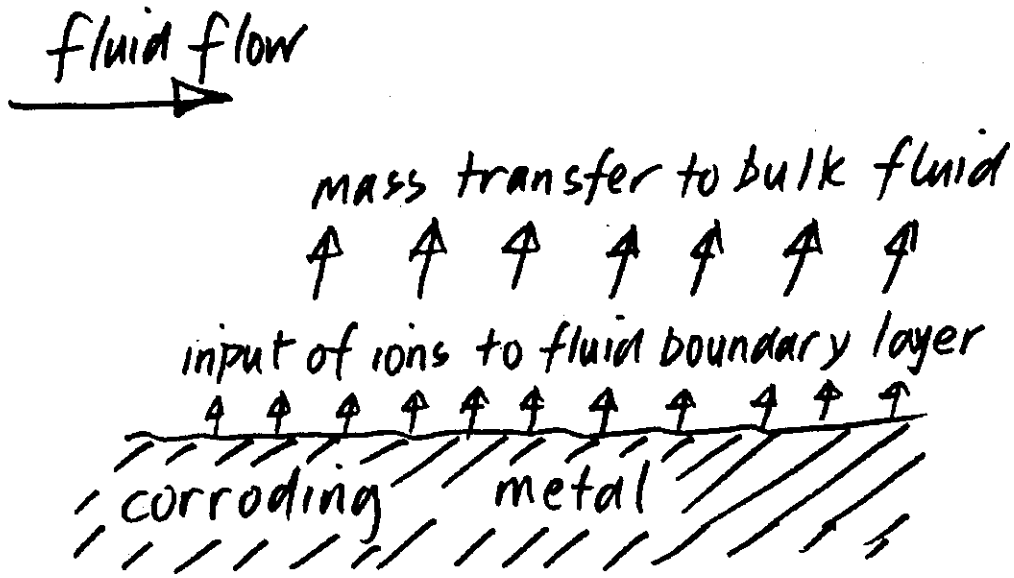
Impeller lasted ~ 2 years in oxidizing conditions; after switch to reducing conditions, it lasted ~ 3 weeks!

Most metals/alloys are susceptible to erosion-corrosion.

Metals that rely on protective surface film for corrosion protection are particularly vulnerable, e.g.:

Al
Pb
SS.

Attack occurs when film cannot form because of erosion caused by suspended particles (for example), or when rate of film formation is less than rate of dissolution and transfer to bulk fluid.



Erosion-Corrosion found in:
- **aqueous solutions;**
- **gases;**
- **organic liquids;**
- **liquid metal;**

If fluid contains suspended solids, erosion-corrosion may be aggravated.

Vulnerable equipment is that subjected to high-velocity fluid, to rapid change in direction of fluid, to excessive turbulence . . .

viz. equipment in which the contacting fluid has a very thin boundary layer
- **high mass transfer rates.**

Vulnerable equipment includes:

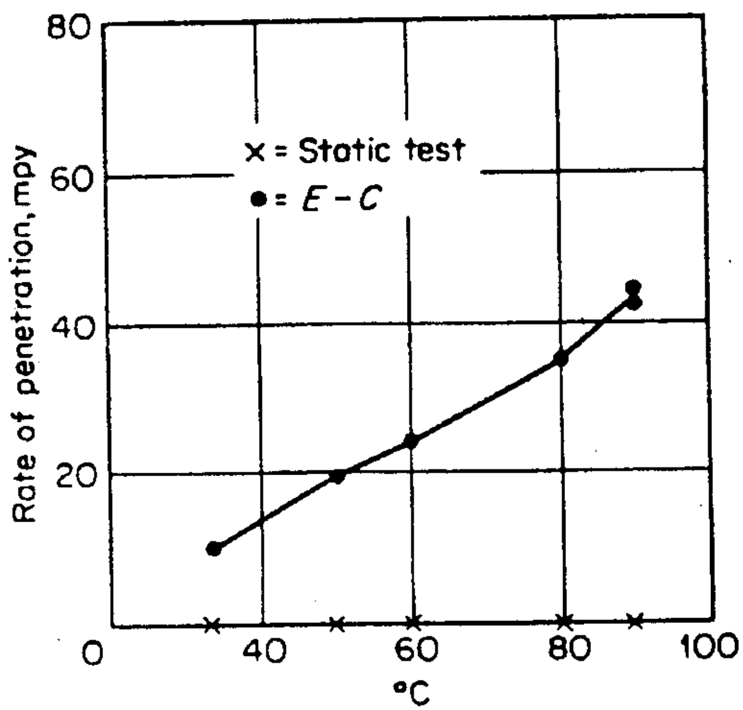
- **pipes (Bends, elbows, tees);**
- **valves;**
- **pumps;**
- **blowers;**
- **propellers, impellers;**
- **stirrers;**
- **stirred vessels;**
- **HX tubing (heaters, condensers);**
- **flow-measuring orifices, venturies;**
- **turbine blades;**
- **nozzles;**
- **baffles;**
- **metal-working equipment (scrapers, cutters, grinders, mills);**
- **spray impingement components;**
- **etc.**

Surface film effects

Protective corrosion-product films important for resistance to erosion-corrosion.

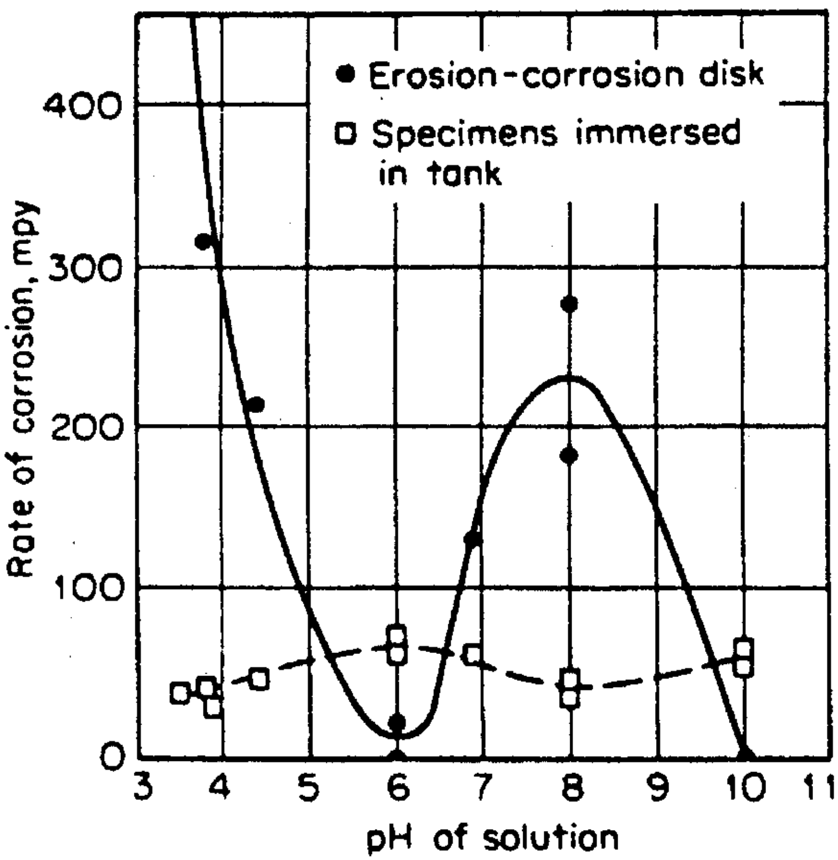
Hard, dense, adherent, continuous films give good resistance, provided that they are not brittle and easily removed under stress.

Lead sulphate film protects lead against <u>DILUTE</u> H_2SO_4 under stagnant conditions, but not under rapidly moving conditions.



Erosion corrosion of hard lead by 10% sulphuric acid (velocity 39 ft/sec).

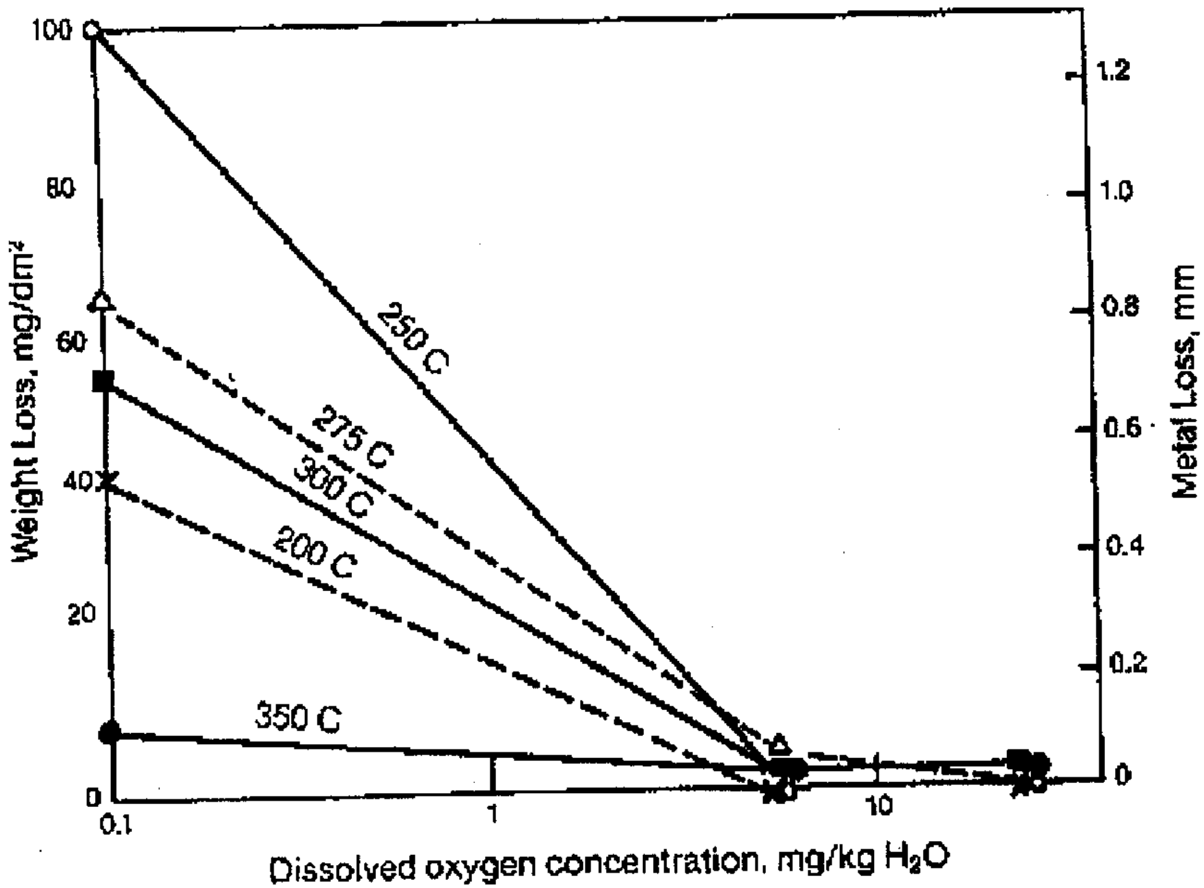
pH affects films in erosion-corrosion of low-alloy steel.



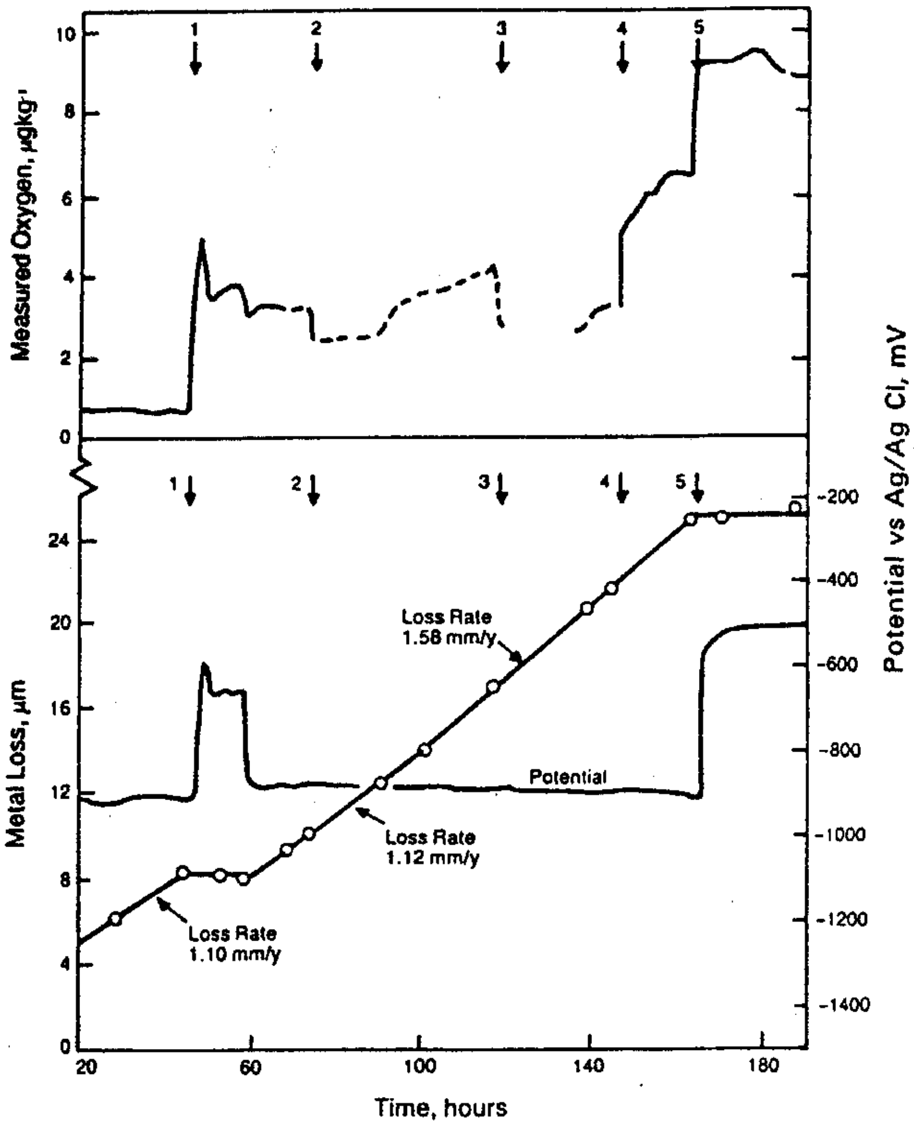
Effect of pH of distilled water on erosion of carbon steel at 50°C (velocity 39 ft/sec).

Scale generally granular Fe_3O_4 (non-protective). But at pH 6 & pH 10, scale $Fe(OH)_2/Fe(OH)_3$ . . . hinders mass transport of oxygen and ionic species.

N.B. Dissolved O_2 often increases erosion-corrosion . . .
e.g. copper alloys in seawater. . . BUT . . . on steels, dissolved O_2 will inhibit erosion-corrosion . . . utilized in boiler feedwater systems.



Effects of temperature and dissolved O_2 on the weight-loss of AISI 304 stainless steel exposed for 800 hours in flowing water at 3.7 m/s.



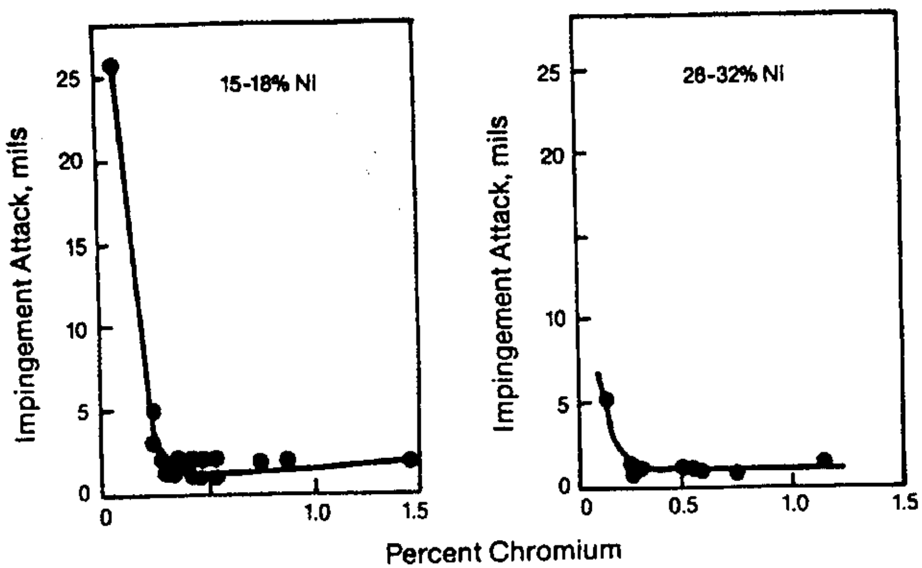
Effect of oxygen dosing on erosion-corrosion and potential of carbon steel in water at 150°C, pH_{25} = 7.8.

Good resistance of Ti to erosion-corrosion in:
- **seawater;**
- **Cl^- solutions;**
- **HNO_3;**

and many other environments.

Resistance depends on formation and stability of TiO_2 films.

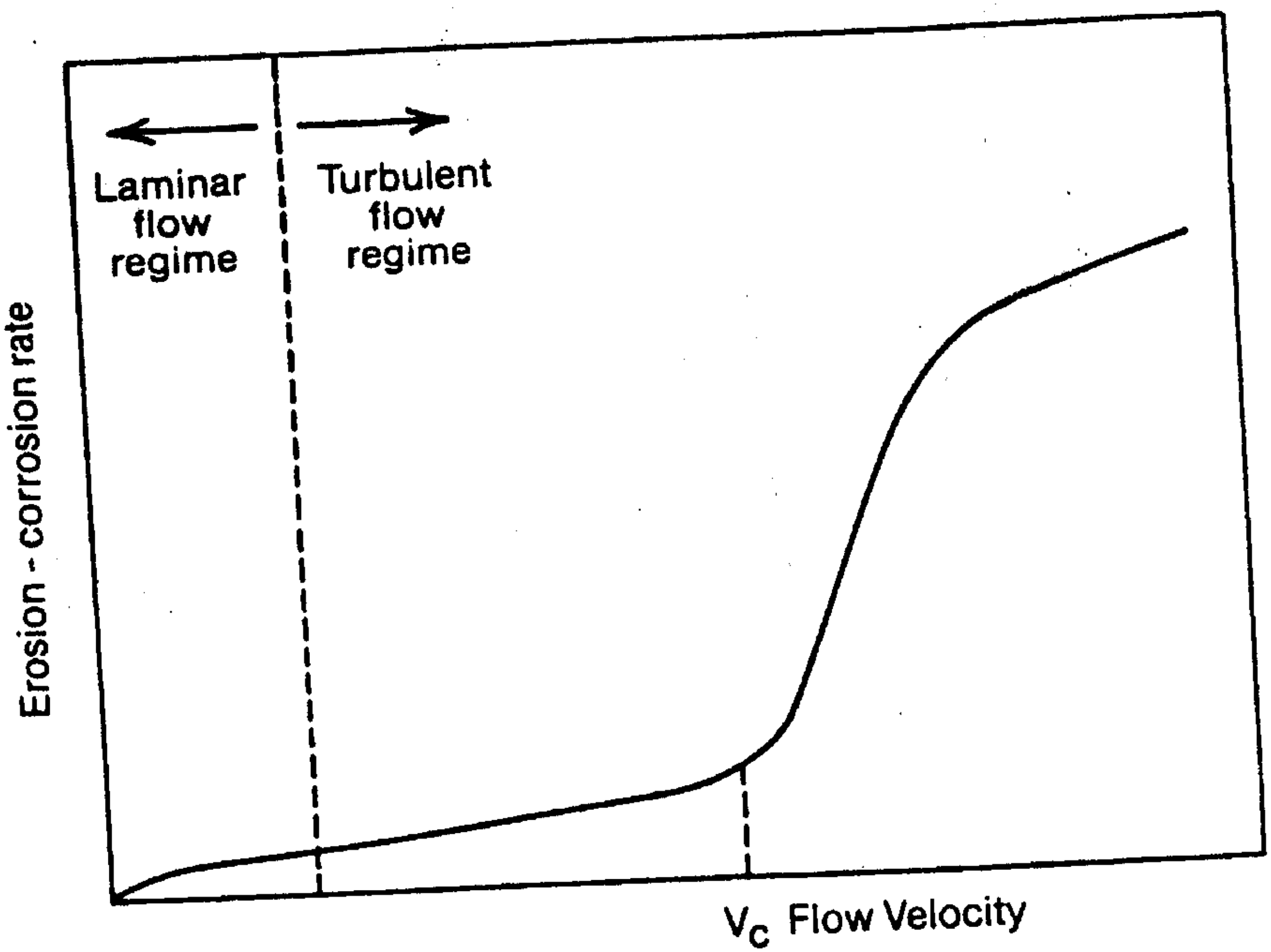
Chromium imparts resistance to erosion-corrosion to:
- **steels;**
- **Cu alloys.**



Effect of chromium additions on seawater impingement-corrosion resistance of copper-nickel alloys. 36 day test with 7.5 m/s jet velocity; seawater temperature: 27°C.

Such tests have led to the marketing of a new alloy for condenser tubes . . "CA-722" . . . previously "IN-838" . . . with constituents . . . Cu-16Ni-0.4Cr.

Velocity Effects



Schematic showing the effect of flow velocity on erosion-corrosion rate.

N.B. Turbulent flow regime for $V < V_c$ is sometimes called "Flow-Assisted Corrosion" regime.

Relationship between flow velocity, v, and erosion-corrosion rate, w, may be written as . . .

$$w = kv^a$$

where k and a are constants that depend on the system.

DISCUSS: What happens when v = 0 ?

How do we express no dependence on velocity?

The exponent "a" varies between . . .

0.3 (laminar flow) and

0.5 (turbulent flow)...

occasionally reaching > 1.0 for mass transfer effects.

For mechanical removal of oxide films (spalling), the fluid shear stress at the surface is important, and a > 1.0 . . . (may reach 2 - 4).

Erosion-Corrosion in Carbon Steel and low-alloy steels

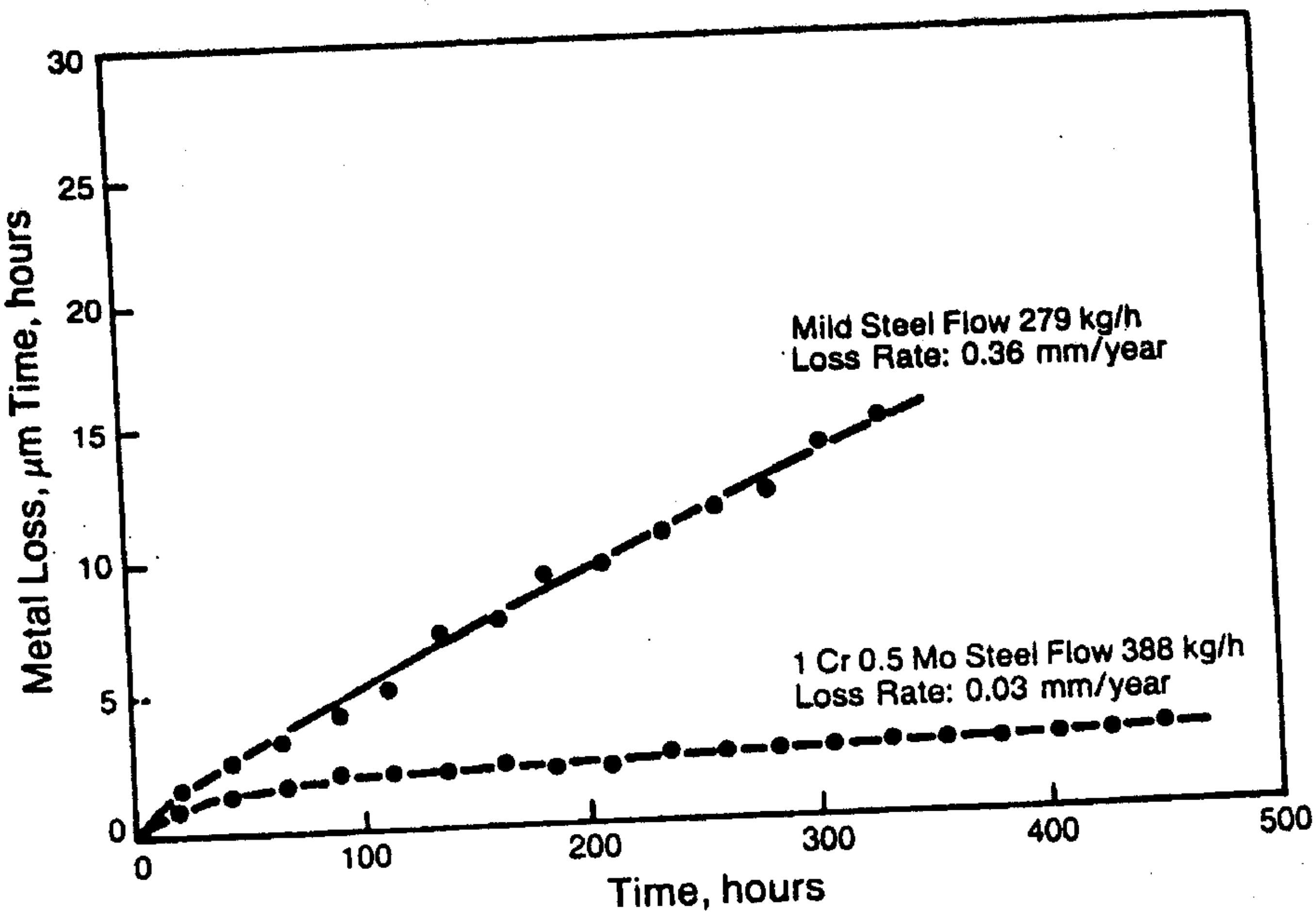
N.B. these materials are used extensively in boilers, turbines, feed-water heaters in fossil & nuclear plants.

High velocities occur in single-phase flow (water) and two-phase flow (wet steam).

Single-phase E-C seen in H.P. feedwater heaters, SG inlets in AGRs, feedwater pumps.

Two-phase E-C more widespread . . . steam extraction piping, cross-over piping (HP turbine to moisture separator), steam side of feedwater heaters.

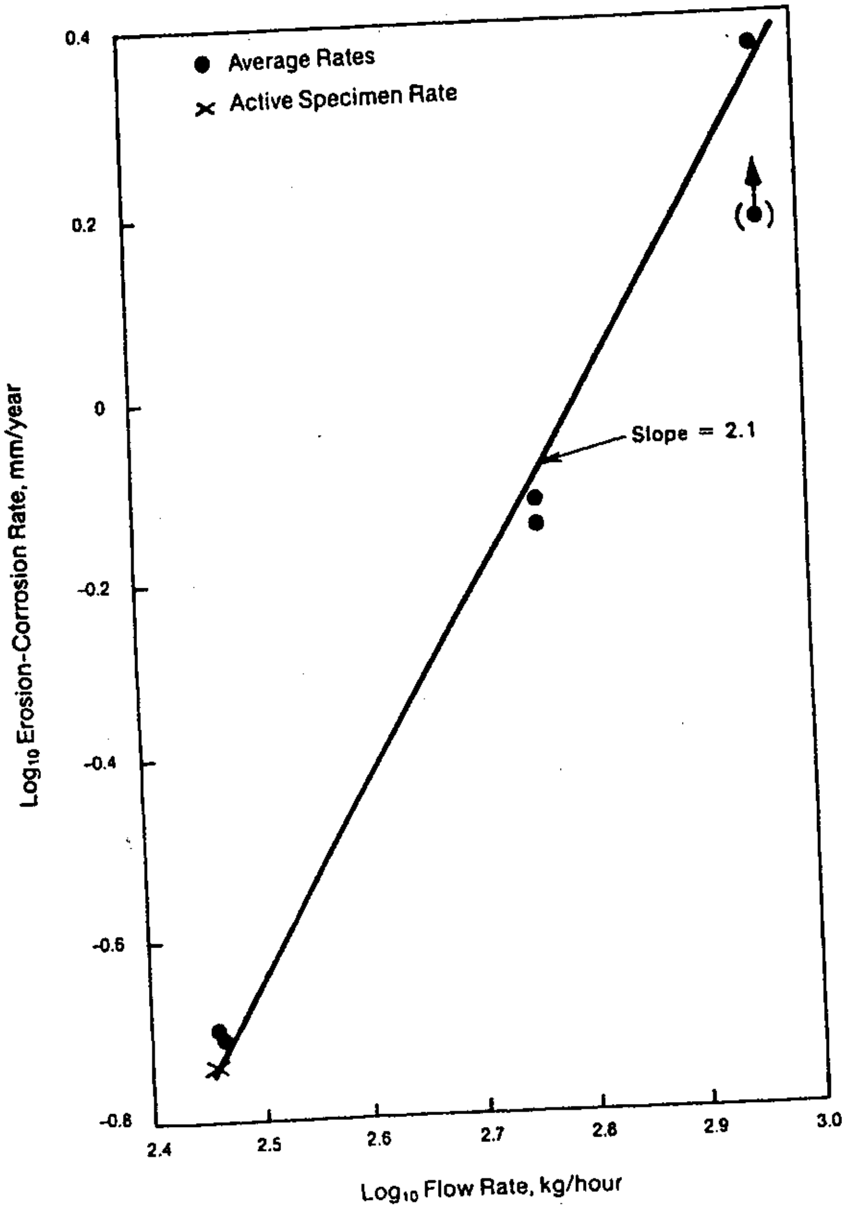
Material effects - low alloy steel . . .



Cr additions reduce E-C.

Erosion-corrosion loss as a function of time for mild steel and 1 Cr 0.5 Mo steel in water (pH_{25} = 9.05) flowing through an orifice at 130°C.

Flow dependence (single phase)...



Erosion-corrosion rate of carbon steel as a function of flow rate deoxygenated water orifice at pH 9.05 and at 149°C.

Accepted mechanism ... for E-C of C.S. in high temperature de-oxygenated water . . .

- **magnetite film dissolves reductively**

$$Fe_3O_4 + (3n-4)\ H_2O + 2e \longrightarrow 3Fe(OH)_n^{(2-n)} + (3n-4)H^+$$

- **high mass transfer rates remove soluble Fe II species;**
- **metal dissolves to try and maintain film.**

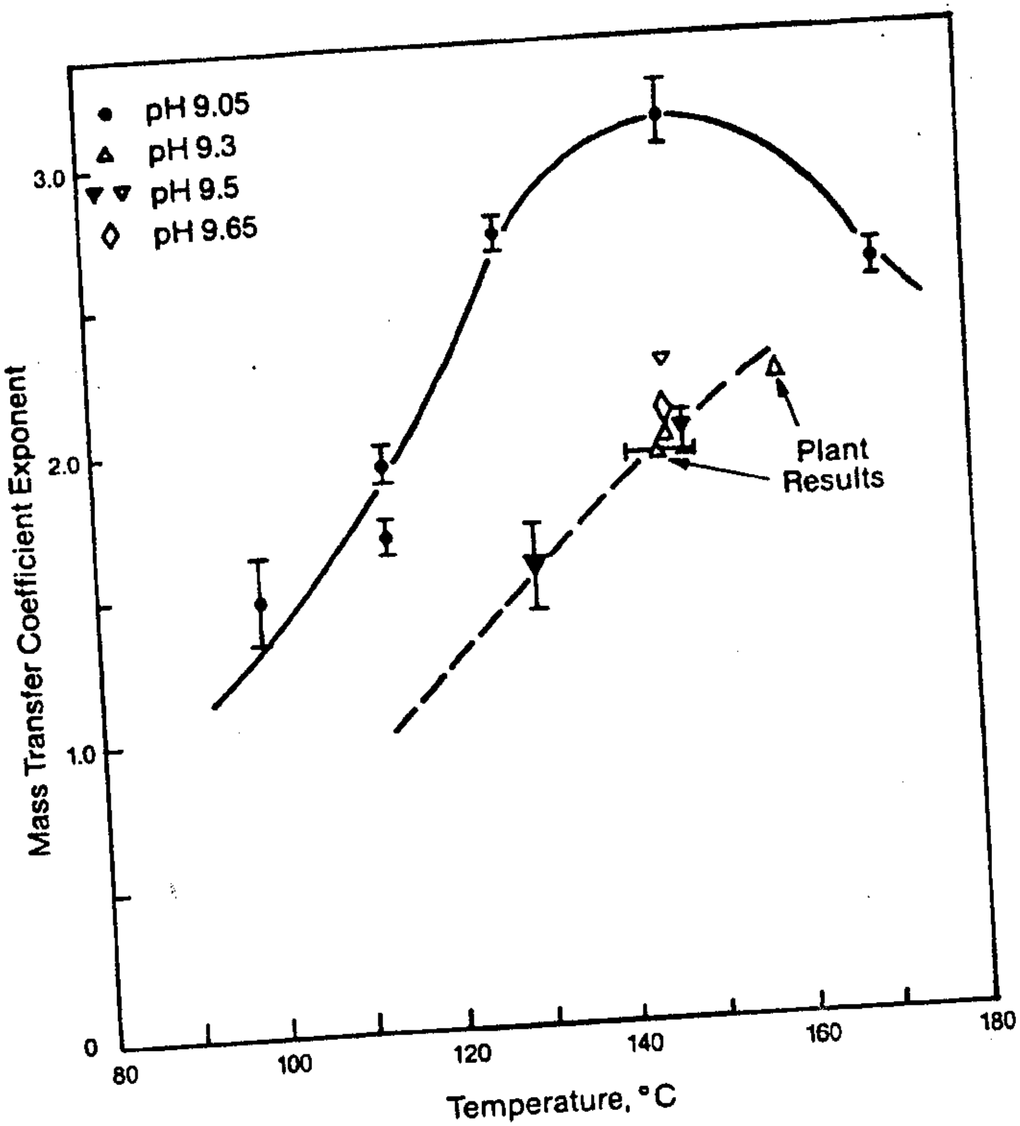
Mass transfer characteristics correlated by expressions such as...

$$Sh = kRe^a\,Sc^b = \frac{kd}{D}$$ Sh = Sherwood Number

$$Re = \frac{dv\rho}{\mu}$$ Re = Reynolds Number

$$Sc = \frac{\mu}{\rho D}$$ Sc = Schmidt Number

Temperature and pH dependence for single-phase E-C of CS . . .



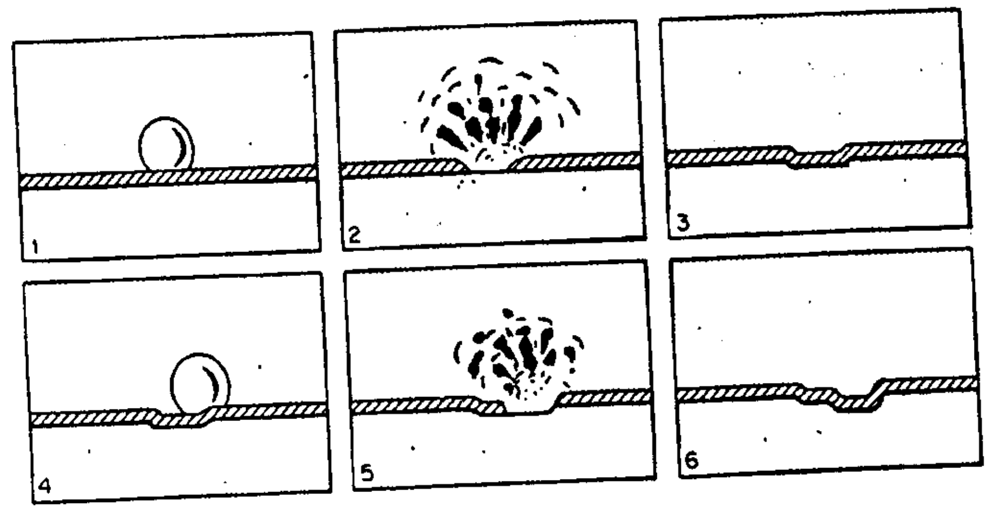
Effect of temperature on the exponent of the mass transfer coefficient for the erosion-corrosion of carbon steel in flowing water at various pHs.

Prevention of Erosion-Corrosion

- design (avoid impingement geometries, high velocity, etc.);
- chemistry (e.g., in steam supply systems . . . for CS or low-alloy steel add O_2, maintain pH > 9.2, use morpholine rather than NH_3);
- materials (use Cr-containing steels);
- use hard, corrosion-resistant coatings.

NOTE:

Cavitation damage similar effect to E-C: mechanical removal of oxide film caused by collapsing vapour bubbles.



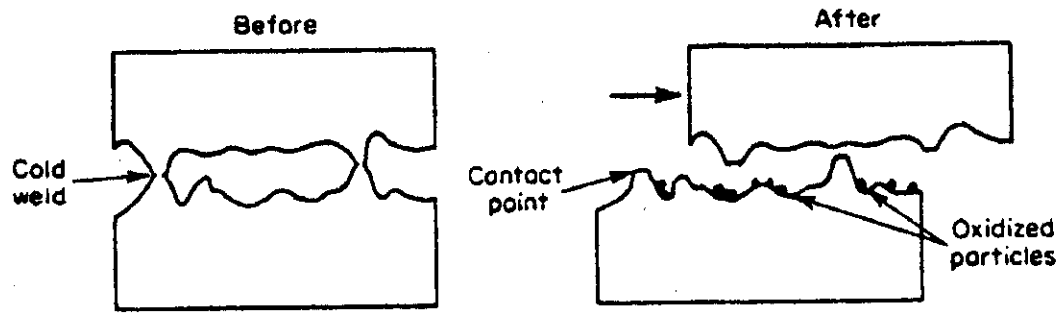
Schematic representation of steps in cavitation.

High-speed pressure oscillations (pumps, etc.) can create shock waves > 60,000 psi. Surface attack often resembles closely-spaced pitting.

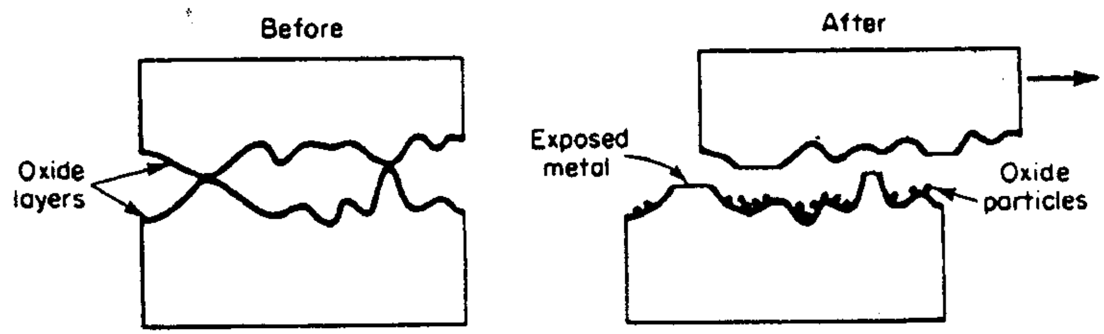
FRETTING CORROSION

Similar to E-C but surface mechanical action provided by wear of another surface . . . generally intermittent, low-amplitude rubbing.

Two theories . . . with same overall result . . .



Schematic illustration of the wear-oxidation theory of fretting corrosion.



Schematic illustration of the oxidation-wear theory of fretting corrosion.

Effects in terms of materials COMBINATIONS

Fretting resistance of various materials

Poor	Average	Good
Aluminum on cast iron	Cast iron on cast iron	Laminated plastic on gold plate
Aluminum on stainless steel	Copper on cast iron	Hard tool steel on tool steel
Magnesium on cast iron	Brass on cast iron	Cold-rolled steel on cold- rolled steel
Cast iron on chrome plate	Zinc on cast iron	Cast iron on cast iron with phosphate coating
Laminated plastic on cast iron	Cast iron on silver plate	Cast iron on cast iron with coating of rubber cement
Bakelite on cast iron	Cast iron on silver plate	Cast iron on cast iron with coating of tungsten sulfide
Hard tool steel on stainless	Cast iron on amalgamated copper plate	Cast iron on cast iron with rubber gasket
Chrome plate on chrome plate	Cast iron on cast iron with rough surface	Cast iron on cast iron with Molykote lubricant
Cast iron on tin plate	Magnesium on copper plate	Cast iron on stainless with Molykote lubricant
Cast iron on cast iron with coating of shellac	Zirconium on zirconium	

Source: J.R. McDowell, ASTM Special Tech. Pub. No. 144, p. 24, Philadelphia, 1952.

Prevent fretting corrosion...

- lubricate;
- avoid relative motion (add packing, etc.);
- increase relative motion to reduce attack severity;
- select materials (e.g., choose harder component).