

Flow Accelerated Corrosion

Synergistic effects of the influencing parameters

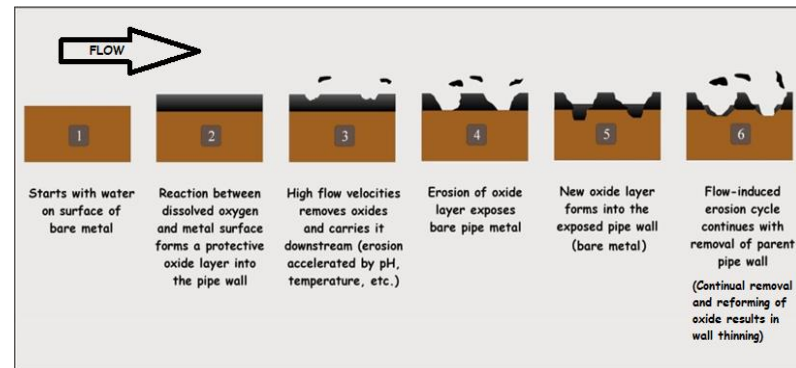
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Subject Matter Expert*

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FAC?

Its main difference with Erosion-Corrosion? When came into Owner's attentions?

- ▶ Flow Accelerated/Assisted Corrosion (FAC), is a significant damage mechanism common to CS materials in power plants and been a concern therein for many years. The term is in fact originated by Electric Power Research Institute (EPRI) for a condition that the industry has previously labeled with the more generic term erosion-corrosion. In the corrosion literatures, since both FAC and Erosion-Corrosion (E/C) damages involve destruction of a protective oxide film on the inside pipe wall, they have been frequently used interchangeably to describe similar material degradations mechanisms, which is incorrect.
- ▶ The FAC process can be described by two distinct mechanisms:
 - The first mechanism is dissolution of iron oxides and producing of soluble iron species (Fe^{2+}) at the oxide/water interface.
 - The second mechanism is the transfer of the dissolved corrosion products to the bulk flow in the direction of flow across the diffusion boundary layer.Therefore, FAC is considered primarily a corrosion dominated process followed by wear mechanism aided by mass transfer of fluid (water or wet steam) mainly on flow turbulences areas resulting is wall thinning and rupture in CS piping systems and process equipment.
- ▶ This is a subtle difference between principles of FAC and various Erosion-Corrosion (E/C) mechanism.
 - In the E/C-process the film is removed from the surface predominantly by mechanical means (primarily erosion dominated mechanism) and then further corrosion occurs. FAC is vice-versa.
- ▶ After Surry Power Station feedwater pipe rupture in December 1986 in US, industry paid particular attention to this damage mechanism and since then started developing and implementing monitoring programs to prevent the rupture of Carbon Steel piping due to this damage.



Simplified mechanism for FAC [1]

Why it is still a concern?

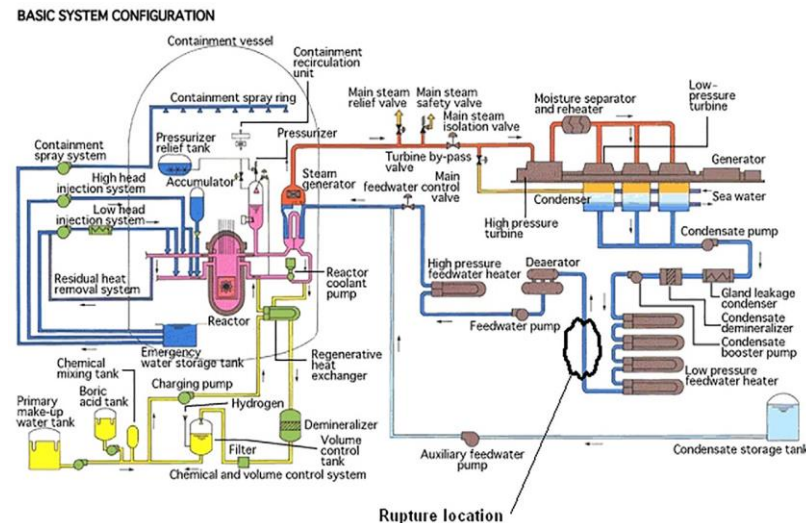
- ▶ Although many researches are conducted on this issue for over 40 years, and the main influencing parameters are well recognized, major failures are still occurring at the same locations that were found in 1980s and 1990s.

- ▶ Power plant owners believe there will be three major reasons why FAC problems are still being encountered or seems fading away in the minds of plant operating management at many facilities:
 1. Many retirements in the power industry (the main contributing factor)
 2. The new personnel simply do not understand the FAC and the importance of FAC control.
 3. The functional relationships and positive combinations effects between:
 - the influencing environmental variables (i.e., fluid temperature, pH, and oxygen concentrations)
 - hydrodynamic severity of the flow (i.e., mass transfer rate),
 - Metallurgical variable (i.e., the MOC mainly the amounts and impacts of alloying elements in the steel, in particular chromium, molybdenum, and copper).

Are not very well appreciated despite accessing to expensive predictive tools. In fact, predictive tools will be useful if the synergistic effects of various FAC influencing parameters are well understood.

Areas at High Risk in Conventional Power Plants

- ▶ Generally, areas at highest risk of FAC damage in conventional fossil power plants included the following (S: single phase and T: Two phase).
 - **Low-pressure feedwater piping system (normally before Deaerator)**, typically at expander in piping between feedwater heater and deaerator, discharge piping from low pressure feedwater heaters, low pressure piping at 90degree elbow (S)
 - **Feedwater piping around Deaerator and Boiler Feedwater Pumps**, typically at the elbow/tees of the deaerator outlet piping to condensate booster pumps, also at boiler feedwater pump suction/discharge piping at elbow, reducer, tees including the discharge recirculation piping after control valves as well as the balancing lines of boiler feedwater pump (S)
 - **Feedwater controlling system typically at orifices, thermowells, and regulating valves** (S)
 - **Steam attemperator supply piping and downstream of spray control valve** (S, T).
 - **HP and LP heater drains piping to condensers including emergency (high level) drain piping from HP heater to deaerator or LP heater typically before/after control valves**, or at the reducers/expanders, elbows, tees, and valve bodies (S, T). This is the most prevalent area, where about 60% of organizations record problems.
 - **LP and IP evaporators and LP, IP and HP economizer tubing** (S, T)
 - **HP and LP feedwater heater shells** (generally near cascading drains), also its vent lines to condensers typically at elbows (T)
 - **High pressure (HP) feedwater heater tubes and tube sheets fabricated in carbon steel** (S)
 - **Deaerator shells near to fluid entry piping** (T)
 - **Turbine exhaust diffuser and Air-Cooled Condensers** (T)



*Location of pipe rupture at Mihama unit 3
(accident of August 9, 2004) [10]*

FAC types and their associated Corrosion reactions

▶ Single phase FAC (water flowing streams):

▪ Corrosion reaction of iron with water under anaerobic conditions and formation of oxide film:

- $\text{Fe} + 2\text{H}_2\text{O} \rightarrow \text{Fe}^{2+} + 2\text{OH}^- + \text{H}_2 \uparrow$ (reaction of iron with water – corrosion reaction)
- $\text{Fe}^{2+} + 2\text{OH}^- \leftrightarrow \text{Fe}(\text{OH})_2 \downarrow$ (formation of ferrous hydroxide)
- $3\text{Fe}(\text{OH})_2 \leftrightarrow \text{Fe}_3\text{O}_4 \downarrow + 2\text{H}_2\text{O} + \text{H}_2 \uparrow$ or $3\text{Fe} + 4\text{H}_2\text{O} = \text{Fe}_3\text{O}_4 \downarrow + 4\text{H}_2 \uparrow$ (formation of magnetite).

▪ Fe^{2+} (soluble ferrous species) and generated hydrogen diffuses through porous magnetite into water interface. Hydrogen would also diffuse into the carbon steel.

▪ Dissolution and reduction of magnetite at the external interface between the oxide and the water, $\text{Fe}_3\text{O}_4 \downarrow + 2\text{H}_2\text{O} + \text{H}_2 \leftrightarrow 3\text{Fe}(\text{OH})_2$

(or through this reaction when hydrazine is used: $2\text{Fe}_3\text{O}_4 \downarrow + \text{N}_2\text{H}_4 + 12\text{H}^+ \leftrightarrow 6\text{Fe}^{2+} + 8\text{H}_2\text{O} + \text{N}_2$).

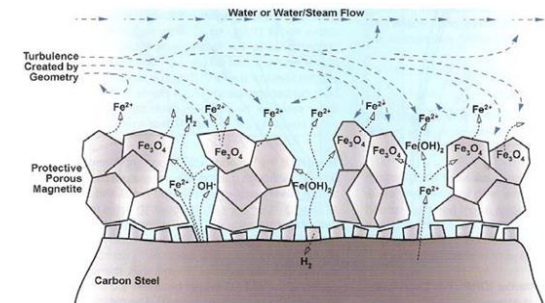
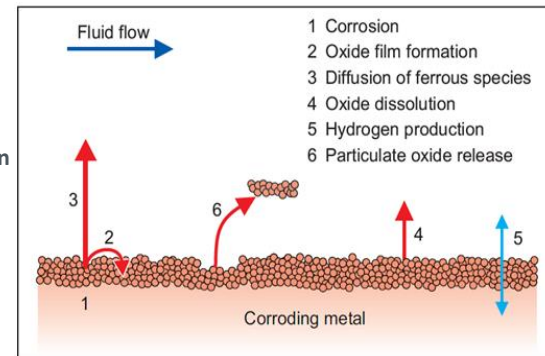
(or through this reaction when ammonia is used: $3\text{Fe}_3\text{O}_4 \downarrow + 2\text{NH}_3 + 18\text{H}^+ \leftrightarrow 9\text{Fe}^{2+} + 12\text{H}_2\text{O} + \text{N}_2$).

▪ Transfer of soluble iron species towards the flowing water and diffusion of hydrogen into atmosphere through the steel.

▶ Two phase wet steam FAC (water-steam mixture flowing streams):

In two-phase FAC process, the protective oxide film is not mechanically removed. Rather, the oxide is dissolved in a flowing fluid that is unsaturated in the dissolving species (i.e., Fe^{2+}) and then either partially prevented from forming and allowing corrosion of unprotected surface or the formation rate of protective layer lowered very quickly to a situation where the oxide thickness is lesser than required to provide internal corrosion protection hence allowing corrosion and thinning of metal to proceed to the point of failure. The oxide dissolution mechanism in wet steam is similar to the single-phase FAC mechanism (as mentioned above). Moisture in the wet steam is essential to dissolve the oxide film by electrochemical reactions, so this degradation has not been observed in pipe carrying dry steam (100% steam quality).

▶ **The quicker the dissolved oxide layer being removed by mass transfer** (i.e., by means of more turbulent flow conditions at local geometries) **means a faster overall FAC corrosion process** and so the thinner remaining magnetite on the surface **until complete rupture**.

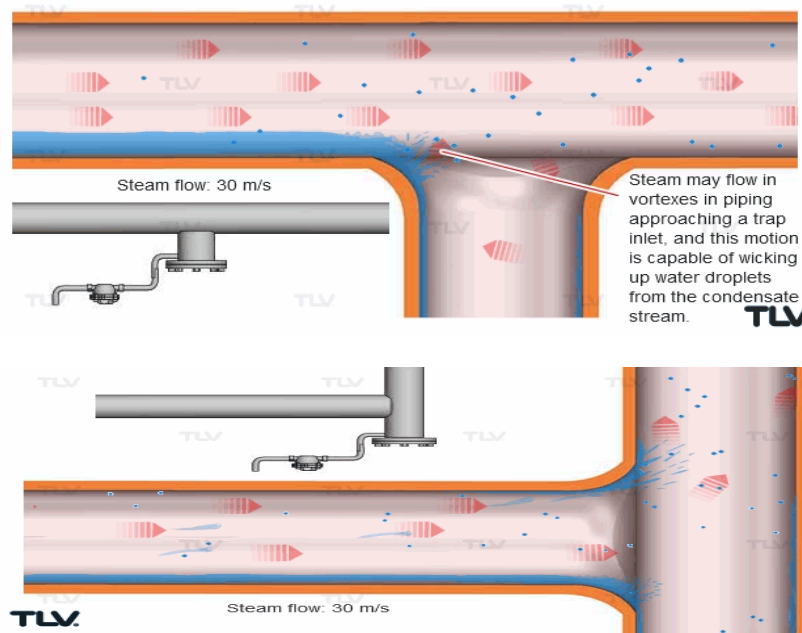


Chemical reactions involved in FAC process [1,2]

LDI-Corrosion variant of Two phase FAC

- ▶ In two phase wet steam system, the liquid generally flows in a thin layer near the inside wall surface (typically at the bottom of the pipe), while the vapor/steam forms the core of the flow and moves much faster than the liquid phase. As a result of this velocity difference, liquid droplet can form and carried over with steam directly impinging the oxide film on the inside surface. This impingement could produce a matrix of cracks and subsequent fatigue failure of the oxide film thus exposing underlying bare material to corrosion by condensate.
- ▶ In two phase systems, as a function of pH, temperature, and superficial steam velocity, either dissolution or droplet impingement could be the dominating damage mechanism which will be discussed later.

Droplet entrainment and impingement in wet steam



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Single and Dual Phases FAC Damage Morphology

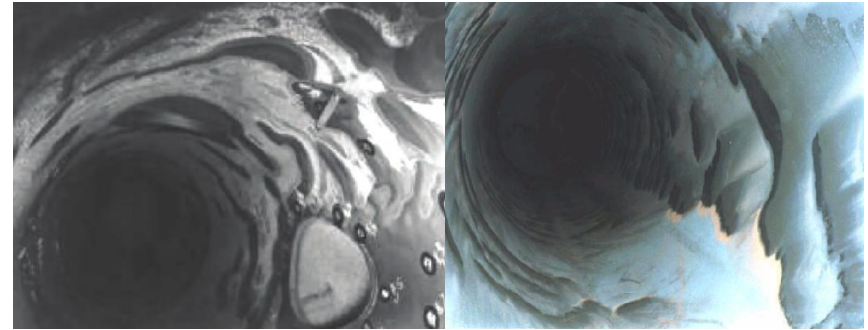
▶ FAC damage morphology

- Single-phase fluid gives rise to an orange-peel effect surface in the direction of flow along with small cavities.
- Two-phase FAC have a tiger-striped black shiny appearance.

(a)



(b)



(a) Orange-peel surface of single-phase FAC [3]

(b) Tiger-striped surface of two-phase FAC [3,4]

FAC rate calculating model (Chexal-Horowitz Model)

▶ **TL (FAC Rate) = F(T) x F(O₂) x F(pH) x F(a) x F(MT) x F(G) x F(AC) [Ref. 26]**

- TL = Thinning Loss
- F(T) = factor for temperature effect
- F(O₂) = factor for oxygen effect
- F(pH) = factor for pH effect
- F(a) = Factor of steam quality also called factor for predicting void fraction (i.e., the area occupied by the vapor divided by the pipe area given the pressure, liquid and vapor mass flow rate, pipe diameter, and pipe orientation). This factor shall only be added for two phase FAC. Without this factor, the calculated FAC rate based on above formula will only address the rate for single-phase FAC.
- F(MT) = factor for mass transfer effect (i.e., function of flow rate and pipe diameter)
- F(G) = factor for geometry effect
- F(AC) = factor for alloy content (i.e., effect of Chromium, Molybdenum, and Copper content)



Environmental Variables
(Water Chemistry factor)



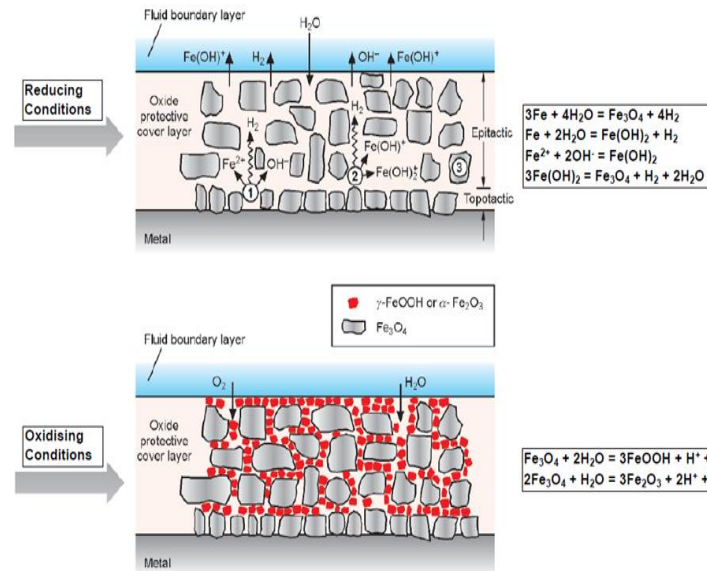
Hydrodynamic Variables



Chemical Composition of Steel
(Metallurgical Variables)

Effect of Dissolved Oxygen Concentration

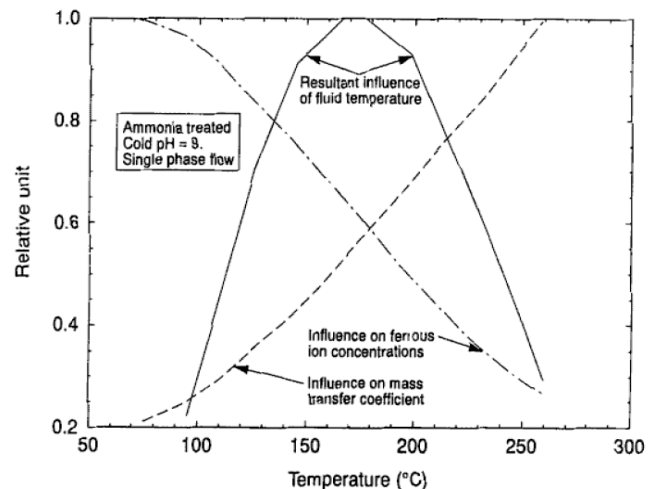
- ▶ In a completely oxygen-free (anaerobic) environment where iron oxides layers cannot be forming, the chances of failure due to FAC are higher therefore, it is critical to have some level of oxygen “in ppb range” in fluid to allow formation and retaining magnetite layer internally for FAC suppression.
- ▶ Under both oxidizing and reducing conditions, the predominant form of protective film on internal surface of a carbon steel component is Magnetite (Fe_3O_4). In all ferrous systems, when enough oxygen is available in the water (i.e., under oxidizing conditions), the dissolved oxygen promotes the formation of hematite (Fe_2O_3) and other types of oxides such as iron hydroxide oxide (FeOOH) at the fluid/metal interface, which is less soluble than the magnetite (Fe_3O_4). Formation of these less soluble oxides plug the pores and porosities in magnetite layer creating a tighter, more stable, and uniform layer where it inhibits the Fe^{2+} ion diffusion from steel surface into the oxide-water interface thus protects the component against FAC attacks.
- ▶ The precise oxygen level required to prevent FAC damage depends on other factors, mainly pH (more specifically the equivalent-pH25°C) and temperature of fluid.



Growth of iron oxides/hydroxides protective layers under oxidising and reducing conditions. Adapted from [7]

Effect of Temperature on FAC

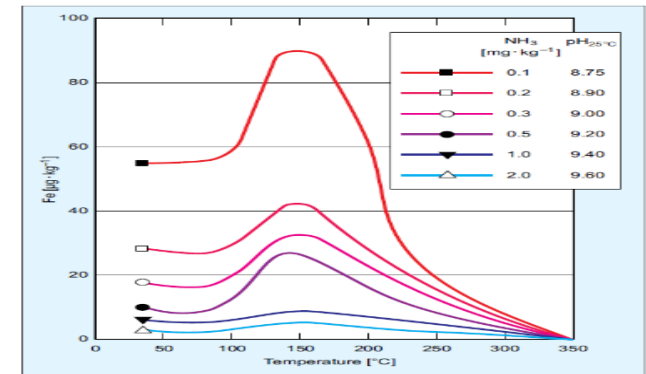
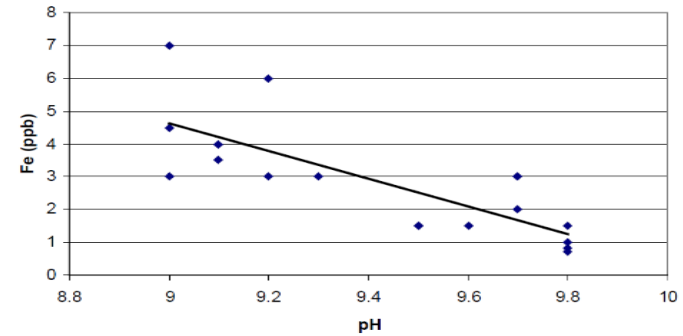
- ▶ The rate of formation, the stability, and adherence of iron oxide layers on carbon steel surfaces are extremely dependent on temperature. At high temperature (typically $>205^{\circ}\text{C}$), the magnetite layer can form quickly even at very low concentration of oxygen and that layer on its own is very stable, dense, and uniform.
- ▶ For single phase FAC, the peaks temperature is within the range of $\sim 140^{\circ}\text{C}$ to 160°C .
- ▶ For two phase FAC, the peak is at 180°C .
- ▶ The FAC risk is none below 93°C and above 232°C (in single phase flow) and 260°C (in two-phase flow).
- ▶ The dependency of FAC to temperature is like a bell shape curve at constant pH:
 - At lower temperature, the capacity of water to remove ferrous ions is high but at the same time the flow viscosity and the ferrous ion diffusivity, which affects mass transfer in the boundary layer, is lower.
 - This means increasing temperature, **increases** the ferrous ions diffusivity into the coolant resulting in a mass transfer coefficient to increase almost linearly.
 - However, by increasing temperature, for which results in formation of a tight and stable iron oxides on the internal surface, the ferrous ion concentration or the solubility of ferrous ions at the oxide-water interface **decreases** almost linearly too.
 - These two effects are competing in nature and result in a bell shaped curve.



Effect of Temperature [5,6]

Effect of pH

- ▶ It is the lower pH (in a reducing environment) in water (single phase flow) which will dissolve magnetite protective layer. Therefore, to preserve this layer and so minimising the corrosion of steel exposed to the high-temperature water for which FAC would be of a concern, general practice is to maintain the equivalent-pH_{25°C} value of high temperature water in alkaline condition but below typically ~10 since the solubility of magnetite increases again above this pH as temperature rises.
- ▶ Similarly, in two-phase flows, the critical parameter is the pH of the liquid phase, not the steam. Increasing pH inhibits the concentration ratio of ferrous ion (i.e., Fe²⁺) at the oxide-water interface and affects dissolution of other dissolved iron species (i.e., Fe(OH)⁺ and Fe(OH)₂) in the solution so promoting the magnetite layer to retain on the surface and therefore suppressing FAC.
- ▶ Experimental results shown that if pH of the solution is allowed to drop to ~9.0 or lower (more precisely lower than ~8.8), the FAC damage becomes increasingly severe. And if **pH maintained >9.5 to 9.8, the FAC attack is considered to be negligible.**



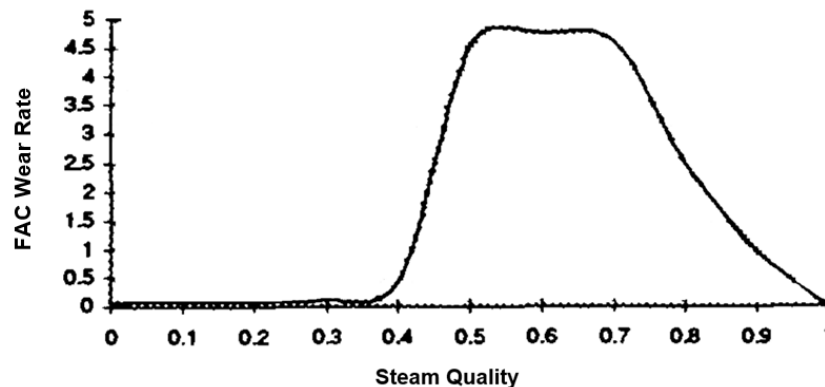
Effects of pH [2,8,9,11]

The Synergistic Effect of pH and Oxygen Level at High Temperature Feedwater on FAC rate

- ▶ General practice is that the feedwater systems are operated with **pH in the range of ~8.8 to ~9.8 depending upon the presence or absence of copper alloys in the circuit.** Experiences established the optimum range of equivalent-pH_{25°C} in mixed metallurgy feedwater systems for FAC mitigation to be in the range of 9.1 to 9.3 and for all ferrous metallurgy between 9.4 to 9.8 [Ref.2].
- ▶ Experimental studies shown that **at 180°C, by increasing pH level of fluid to 9.8, very low DO concentration level (as low as 1 to 2ppb) will be sufficient for FAC suppression on carbon steel materials.** Other experiences indicated **that 5ppb of oxygen in feedwater with pH of 9.5 at 180°C can practically stop FAC** of carbon steels while excessive concentration of oxygen scavengers adversely exacerbating the FAC rate.
- ▶ **Similar to pH, the maximum amount of Oxygen in the system is also depending on presence or absence of copper alloys in the system. In all ferrous metallurgy systems in most combined cycle power plants, oxygen concentrations can be as high as 20ppb without causing any problems while this amount to be reduced practically to 1-2ppb in copper containing systems.**

Effect of Steam Quality in Two-Phase FAC
















- ▶ Test results shown that the FAC rate in a two-phase flow varies with the quality of the steam which is the amount of moisture in the steam [11, 12]. Since presence of water (moisture) is vital for any corrosion mechanism to occur and progressing (i.e., oxides dissolutions), the two phase FAC rate will be zero at 100% quality (dry steam) and will be equivalent to the single-phase (water) flow value at 0% steam [2, 12]. The two-phase FAC rate peaks at some intermediate value of steam quality [12] (typically between ~40% to ~80% at 150°C [2]) as shown in the figure.
- ▶ It must be noted that the LDI-corrosion variant of two phase FAC is very much dependant to steam velocity so that the impact of steam velocity must not be ignored.



FAC Rate versus Steam Quality at 150°C [Ref. 21]

Effects of Component's Geometry

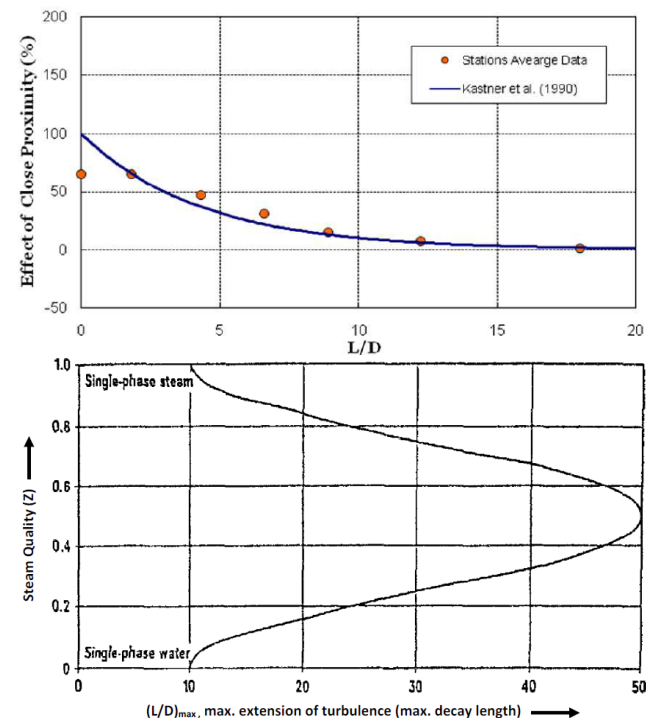
- ▶ Pipe configurations that causes flow hydrodynamic disturbances/turbulences such as elbows, tees, branch connections, reducers, and locations downstream of flow control orifices and valves can result in a further increase in mass transfer coefficient of the ferrous ions into the bulk fluid and thus exacerbating FAC.
- ▶ In general, **turbulence is measured by turbulence intensity** expressed in percentage. And the effect of turbulence on the FAC rate that is represented by the geometry enhancement factor as described by Keller (known also as Keller's Geometry factors).
- ▶ **The more** turbulence intensity means more increase in inside surface roughness and Reynold (Re) number, hence significant increase in MTC (Mass Transfer Coefficient) and therefore the higher FAC rate.
- ▶ A direct linear proportionality has been determined between FAC rate and Reynolds number.

FLOW PATTERN		REFERENCE VELOCITY	K _c
Primary Flow Stagnation Points	 At Pipes	Velocity of Initial Flow (Upstream of Stagnation Obstacle)	1.00
	 At Blades		1.00
	 At Plates		1.00
	 In Pipe Junctions		0.75
	 In Pipe Junctions		0.60
Secondary Flow Stagnation Points	 R/D = 0.5	Flow Velocity	0.52
	 R/D = 1.5		0.30
	 R/D = 2.5		0.23
	 Behind Pipe Joints		0.15
Stagnation Points Due to Vortex Formation	 Behind sharp edged entrances	Flow Velocity	0.16
	 At and behind barriers		0.16
No Stagnation Points	 In straight pipes	Flow Velocity	0.04
	 In loose horizontal turbine seals	Velocity Calculated from Pressure Drop	0.08
Complicated Flow Through Turbines	 In turbine gland seals	Velocity calculated from pressure drop	0.08
	 At and above turbine blades and at drainage collecting rings	Average circumferential blade velocity	0.30

Effect of turbulence on the FAC rate represented by the geometry enhancement factor (Keller's Geometry Factors, K_c) [12,13]

Effects of Proximity Between Piping Components on FAC

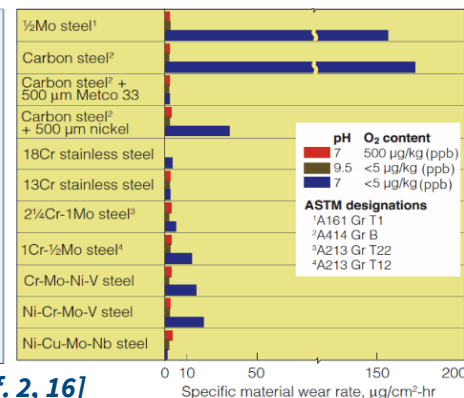
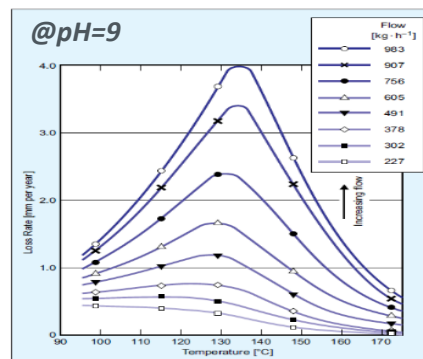
- ▶ In practical applications, the turbulence generated by the upstream piping local geometry component (complex geometries) will be transported with the flow to its downstream proximities so any item(s) located in close-downstream proximities to a turbulent region will be experiencing a higher FAC.
- ▶ Lab experiments and actual gathered plant data in single phase water flowing system shown that bends located within 1D (D is pipe inner diameter) close downstream proximity from a turbulent region could be experiencing a higher FAC rate by 80%. In fact, the average increase in single phase FAC rate was equal to 70% at 0 to 5D proximities and that rate was strongly dependent on the geometry. As an example, the maximum increase in value of FAC rate found to be located within 5D downstream of an orifice.
- ▶ Collected data shown that in single phase water flowing system, the FAC rate reduces to 10% at a distance of $\sim 10D$ and becomes practically negligible for distances greater than $10D$. This shows that the max. extent of turbulence (max. decay length) in single phase water flowing system can go as far as $\sim 10D$, while in Two-phase wet steam system the maximum decay length for closely arranged turbulence-inducing configurations can go as far as maximum $50D$ downstream instead [12] at 50% steam quality and indicated that extent of turbulence is a function of steam quality.



Max Extent of Turbulence [12, 14]

Impacts of Flow Velocity on FAC

- ▶ Various studies concluded that, FAC is not directly dependent on flow velocity and in fact the mean flow rate on its own without considering the impact of other environmental, material, and hydrodynamic variables is not a good indicator of the FAC conditions.
- ▶ At constant pH, the FAC rate increases by increasing flow velocity up to the FAC peak temperature and thereafter the FAC rate drops as a results formation of a tighter and more stable iron oxides on the internal surface at higher temperatures even at very low concentration of oxygen [Ref. 2].
- ▶ Experimental study conducted under different combinations of pH & oxygen on a 180°C water flowing constantly at velocity of 20m/s concluded that the FAC rate of carbon steel material at pH of 9.5 is extremely low even at very low concentration of oxygen (lower than 5ppb) while under similar conditions just by lowering pH to 7, almost 100 times more dissolved oxygen (i.e., ~500ppb) is needed to obtain approximately similar FAC rate as seen at pH of 9.5. This shows by playing with pH and dissolved oxygen level, FAC rate can be much lower even at flow velocities as high as 20m/s in high temperature water [Ref. 16].



[Ref. 2, 16]

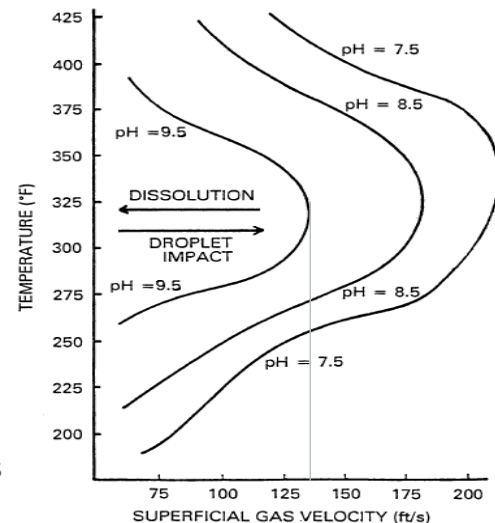
Relationship between Flow Velocity and the required Critical amount of DO Concentration for FAC Suppression with respect to Temperature and pH

pH	Temperature = 140°C (413°K)	Temperature = 180°C (453°K)
pH = 7	DO = ~50-55ppb (at 5m/s, 12m/s, & 30m/s flow velocities)	DO = ~25-30ppb (at 5m/s & 30m/s flow velocities)
pH = 9.2	DO = ~10-12ppb (at 5m/s, 12m/s, & 30m/s flow velocities)	DO = ~8-10ppb (at 5m/s & 30m/s flow velocities)
pH = 9.8	Not tested	DO = ~1-4ppb (at 5m/s & 30m/s flow velocities)

*Experimental testing conducted by
K. Fujiwara et al. [Ref. 17]*

Impacts of Flow Velocity on FAC (cont.)

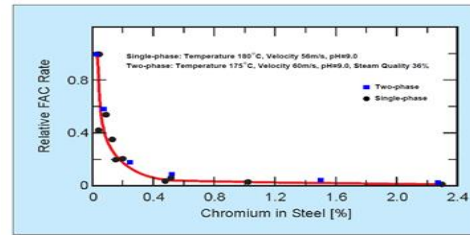
- ▶ Accordingly, it is hard to define an explicit threshold flow velocity for FAC considerations, however, some literatures stated that **FAC normally starts at 3m/s [Ref. 8] in water flowing systems** and below this value, the risk of FAC should generally be negligible. According to literatures, **assuming no variation on other influencing parameters, the FAC rate will be higher by INCREASING flow velocity** as per below:
 - **For single phase water flowing system at $\sim 3\text{m/s} < V < \sim 10\text{m/s}$ [Ref. 8] the rate increasing almost linearly and the dominated mechanism in only by corrosion. At $V > \sim 10\text{m/s}$,** (typically in turbulent areas), the effect is not linear anymore because partial spallation of protective oxide films occurs in bulk fluid as a results of excessive shearing stress at the oxide-water interface the FAC thinning rate could be much more aggressive in such case in comparison. In fact, as velocity increasing, initially a mixture of corrosion and erosion mechanism occurs until the dominating mechanism becomes only by erosion (no more called FAC).
 - **For two phase wet steam flowing systems,** either dissolution or droplet impingement (i.e., the LDI-corrosion variant mechanism of two-phase FAC) could be the dominating damage mechanism as a function of pH, temperature, and superficial gas/steam velocity as shown in the figure. Initially it will be LDI-Corrosion dominated mechanism as a results of partial spallation of corrosion products until full erosion domination as velocity increases.
 - **In wet steam systems with extremely high velocity typically exceeding $\sim 200\text{m/s}$ [Ref. 5],** (this threshold could varies depending on the diameter and density of water droplets), the dominated mechanism of thinning is going to be by pure mechanical erosion (called LDI-erosion) which should not be called FAC anymore. The thinning rate varies with the diameter and density of water droplets in steam but goes on increasing with increasing steam velocity. The LDI mechanical thinning rates are much higher compared to those from FAC and/or LDI-Corrosion.



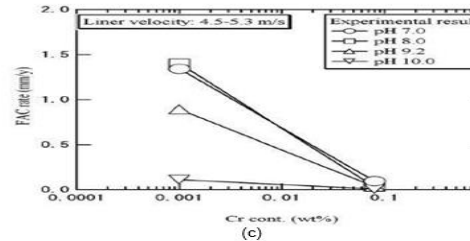
Impact of pH, Temperature and Steam Velocity on two-phase FAC dominated mechanism [Ref. 15]

Effect of Alloying Content (Metallurgical Variables)

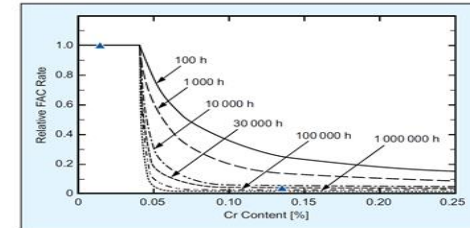
- ▶ In general, higher the Chromium, Molybdenum, and Copper Content (mainly Chromium) resulting much LOWER FAC rate to both single phase and two-phase mechanisms including resistivity to LDI erosion/corrosion (which is a variant mechanism of two-phase FAC) in water-steam mixture flow.
- ▶ Experimental studies concluded that Chromium has the largest effect on oxide film stability, and even trace levels of chromium, on the order of 0.1% can significantly reduce the FAC rate [Ref. 20].



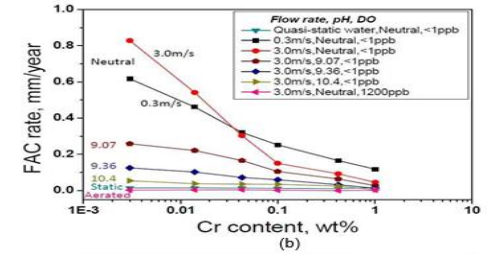
(a)



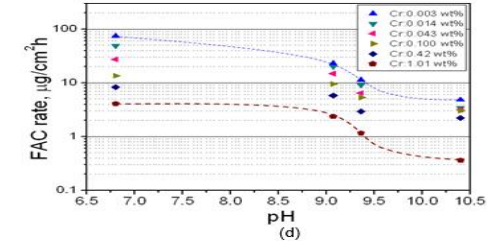
(c)



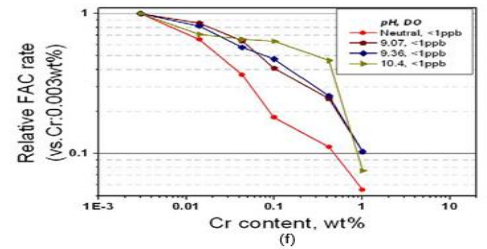
(e)



(b)



(d)



(f)

Effect of Alloying Content (cont.)

- ▶ Other experiments revealed that the use of low alloy steels with 1% to 2% chromium instead of plain carbon steel (such as P11 or P22 Cr-Mo materials) could reduce the FAC rate by a factor of 4 to a factor of 10 or more [Ref. 20] and stainless steels with 12% or greater chromium content are considered practically immune and inherently not prone to FAC [Ref. 5, 20].
- ▶ Huijbregts [Ref. 19], suggested the steel with $\text{Cr-equivalent} = \text{Cr} + 1.4 \text{ Cu} + 0.3 \text{ Mo} - 0.3 \text{ C} > 0.09$ will provide sufficiently high FAC resistivity (alloying elements are described with their weight percentages).
- ▶ Ducreux and Huijbregts [Ref. 19] suggested fractional reduction (FR) correlations of FAC caused by additions of chromium, molybdenum, and copper alloying elements as below:
Ducreux FR (FAC) = $(83\text{Cr}^{0.89}\text{xCu}^{0.25}\text{xMo}^{0.2})^{-1}$
Huijbregts FR (FAC) = $(0.61 + 2.43\text{Cr} + 1.64\text{Cu} + 0.3\text{Mo})^{-1}$
Where Cr, Mo, and Cu are described with their weight percentages.

FAC Prevention and Design Considerations of the Welds

▶ FAC Prevention and Design Considerations of the Welds

- Knowing the benefits of chromium additions for improving FAC resistivity, where FAC is considered a concern, good industry practice suggests the deposited weld metals to overmatch the base materials chemical composition, particularly its chromium content.
- It is recommended to ensure minimum Cr-equivalent of the deposited weld metal exceeding 0.09, similar to what has been suggested for the steels, in order to obtain a sufficiently high FAC resistant weld too.
- It is also important to ensure correct design of the weld root geometry, ensuring no excessive protrusion of the root for which it could cause turbulence and therefore an increase in FAC on the weld and its downstream proximities.

Case Studies and Recommended Design Optimization for FAC Affected Area

- ▶ B. Chexal & J. Horowitz et al. [26] tested various remedial options listed in the table to verifying the impacts of changing various influencing parameters on increasing plant design life of CS components.
- ▶ As for base case option, they assumed the plant operated for 15 years using ammonia as the pH controlling agent (with the pH of fluid set at 9.2) when a severe single-phase FAC damage was discovered on some CS components.
- ▶ Table presented their conclusions.

Remedial Options	Relative Time to Minimum Allowable Wall Thickness (year)	Impact on increasing the predicted lifetime of the CS components (plant)
Base Case Option - pH 9.2 using Ammonia	1	-
<u>(Option 1)</u> - Increasing pH from 9.2 to 9.6 using the same pH Controlling Chemical agent (i.e., Ammonia)	2.053	105%
<u>(Option 2)</u> - Changing the pH Controlling Chemical agent from Ammonia to Morpholine but keeping the pH the same (i.e., 9.2)	1.654	65%
<u>(Option 3)</u> - Changing the pH Controlling Chemical from Ammonia to Morpholine but increasing pH to 9.3	2	100%
<u>(Option 4)</u> - Keeping the chemistry the same but upgrading carbon steel MOC to P11 (i.e., a Cr-Mo alloy with higher Chromium and Molybdenum)	31	3100% (huge increase)
<u>(Option 5)</u> - Keeping the chemistry and the pipe material the same but increasing Pipe Diameter by one size	1.192	19% (small increase)

Misuse of API RP 14E Erosional Velocity Equation for Prediction of FAC Damage

- ▶ The widespread use of the API RP 14E erosional velocity equation is understood to be as a result of its simplicity and little inputs requirements.
- ▶ The API RP 14E equation only considers the density of fluid in calculating the erosional velocity while many other FAC influential factors such as pipe material (metallurgy), fluid properties (pH, DO etc), pipe geometry, and flow turbulence/regime are not accounted. The equation treats flow lines, production manifolds, process headers and other lines transporting oil and gas similarly in terms of limiting the velocity. However, areas with flow disturbances such as chokes, elbows, long radius bends, and tees, where most of the FAC problems occur, are not differentiated by the API RP 14E equation.
- ▶ Therefore, the API RP 14E equation cannot be simply applied for FAC by just modifying the C-factor.

Conclusions (Most effective remedial actions for FAC preventions)

- ▶ The minimum controlling and/or mitigation measures for the areas or components suspected with high risk of FAC or derived that has been affected by FAC should be as per below considering the most cost-effective option in mind:
 - Avoid using steels with low Cr-equivalents. Generally, to extent design life of carbon steel affected areas or components, it is suggested to replacing them with a grade of material that have Cr-equivalent more than > 0.09 .
 - To adjust and use the most optimum water chemistry conditions particularly pH level, DO level, and temperature in single phase flow as well as steam quality in case of two-phase flow. In mixed metallurgy systems the effect of rise in pH and/or DO level on corrosion of copper-based alloys must be considered.
 - Need to ensure less turbulent and less complex geometry configuration in design (i.e., design improvements that causes less aggressive hydrodynamic disturbances) to minimise the complexity of flow pattern and possibility of turbulence. Also, bearing in mind proximities between piping components in the design.
 - If none of the above are practical, knowing the fact that Austenitic stainless steels are practically immune to FAC and Cr-Mo alloys gives much better performance in compared to carbon steel against FAC [2], therefore, replacing the affected carbon steel materials with Cr-Mo alloys (suggested to have at least 1.25% Cr or higher i.e., grade 11 or 22 materials) or austenitic stainless steels (typically SS304/304L or SS316/316L or better) or application of an austenitic stainless steel coating can practically stop FAC. This will generally be the most optimum solution for preventing two-phase FAC affected areas.
- ▶ For welds, it is also suggested to ensure the deposited weld metal's chromium equivalent are exceeding 0.09 (as we do for base materials too) and to also ensure no excessive root penetrations as it could cause turbulent and therefore an increase in FAC on the weld & its downstream proximities.

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Thank you

Questions?