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Flow Accelerated Corrosion: Forms, Mechanisms and Case Studies

Vivekanand Kain

Materials Science Division, Bhabha Atomic Research Centre, Mumbai
E-mail ID: vivkain@barc.gov.in

Abstract

Flow accelerated corrosion (FAC) is distinct from erosion and is primarily an electrochemical corrosion process aided by chemical dissolution and mass transfer. The forms of erosion including single and dual phase FAC and liquid droplet impingement are discussed and differentiated. The reasons for a maxima being observed in FAC rates at 150-170 °C has been explained as well as high FAC rates owing to an inversion in solubility occurring with pH occurring at temperatures around 300 °C. Experience from examination of FAC affected components establishing signature patterns of single and two phase FAC is presented. FAC control measures are discussed. The data required from laboratory tests is identified and ongoing lab studies to measure solubility of various oxides is presented.

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Keywords: Flow accelerated corrosion, signature pattern, solubility, power plants, overload failure

1.0 Introduction

Flow accelerated corrosion (FAC) causes wall thinning (metal thickness loss) of carbon steel piping, tubing and vessels exposed to flowing water or wet steam. When the thickness of the component reaches values lower than the critical thickness required for supporting the operating stresses, it results in ductile failure of the component. If undetected, the degraded components can suddenly rupture, releasing high temperature steam or water. FAC has caused a large number of failures in piping and equipments in all types of fossil, industrial steam, and nuclear power plants and it is a predominant mode of failure of pipelines in the secondary circuit and has also affected carbon steel pipelines in the primary circuit of light water reactors [1-10].

Deoxygenated single phase water or a water – steam mixture in the secondary circuit leads to the formation of a magnetite film on the ID surfaces of the carbon steel surfaces and it acts as a protective film and protects the

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carbon steel components against corrosion. Such a film forms in the high energy systems (temperatures above 95 °C) over a period of time that is dependent on temperature. FAC is a process by which this normally protective oxide layer dissolves into the flowing stream and the oxide layer becomes thinner and less protective. The oxide layer may be thinned to an extent so as to expose an apparently bare metal surface which otherwise exhibits a black colour, typical of magnetite. Even with the oxide film present on the surface, the rate of dissolution of metal through the oxide film does accelerate with higher velocities. This is a corrosion process the rate of which is enhanced by (electro) chemical dissolution and mass transfer and is not a dominant mechanical process. FAC is thus, an extension of the generalized carbon steel corrosion process in stagnant water. Without proper in-service monitoring, the thinned components typically fail due to overstress from operating pressure. Therefore always a ductile fracture is observed. FAC occurs under both single and two-phase flow conditions. As water is essential to remove the oxide layer by electrochemical reactions, FAC does not occur in lines transporting dry steam.

FAC is distinct from erosion-corrosion and is primarily a corrosion process aided by chemical dissolution and mass transfer. In practice, there may be some contribution from the mechanical factors that lead to removal of corroded scallops on material surface to become loose and flow out with the high velocity process fluid. This might be further accelerating the overall FAC rate but would not become a factor for thinning by itself (i.e. without first the electrochemical dissolution leading to FAC and formation of loosely held scallops). The corrosion rate is first determined by the rate of transfer of ionic species between the surface and the fluid. If the corrosion reaction is rapid and the corrosion product has low solubility in bulk fluid, the corrosion rate is governed by the concentration gradient as shown in eq. 1 (also see Fig. 1), where R is the corrosion rate, k is the mass transfer coefficient, C_W is the concentration of rate limiting species at the metal wall, and C_B is the concentration of rate limiting species in the bulk fluid.

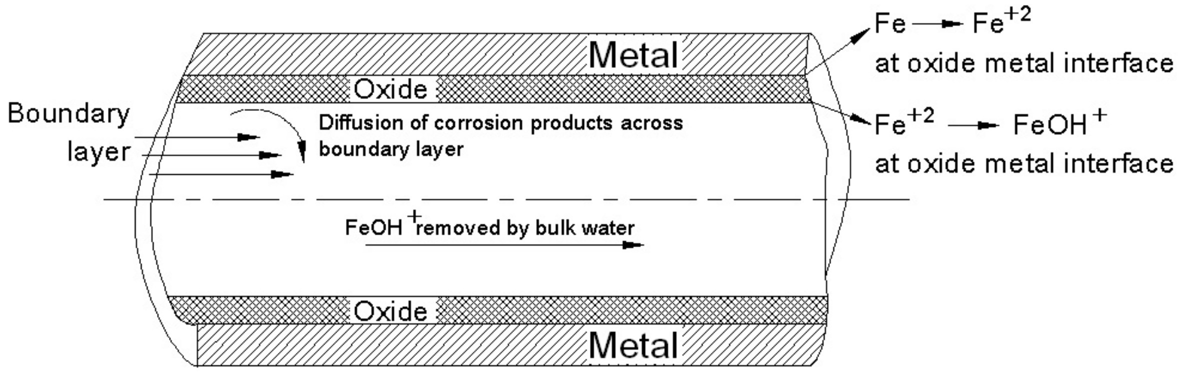


Fig. 1 Schematic of the dissolution of material through surface oxide film and removal of the dissolving species in the bulk water [8].

Flow velocities associated with FAC increases this concentration gradient and thus increases the corrosion rate [8-11]. No evidence of removal of the oxide film purely due to mechanical shear has been found on the FAC damaged surfaces of feed water piping [3]. Erosion corrosion is a form of mechanical degradation that involves corrosion as well as mechanical wear. This occurs on the surface of the material due to the action of numerous individual impacts of solid or liquid particles. Much higher flow velocities are associated with this kind of degradation. Laboratory tests have also shown that the fluid velocities required for mechanical removal of the oxide is higher than that required for dissolution of an oxide layer [3,10, 11]. Definite surface patterns are formed on components undergoing FAC which is a signature of FAC while no such signature is associated with erosion corrosion [8, 12]. Due to erosion corrosion grooves, gullies or rounded holes are formed. This can occur in metals and alloys that are completely resistant to a particular environment at low flow velocities unlike FAC degradation [11-12].

FAC is affected by many parameters, like material composition, temperature, pH, dissolved oxygen content, pipe geometry and flow velocity. FAC is the most destructive corrosion mechanism for high energy carbon steel components in light water reactors [3,6-11]. The maximum in FAC rate appear at ~ 150 °C [3-5, 10]. It has caused rupture of large, medium and small diameter pipelines carrying either single phase (single phase FAC) or two phase (wet steam) flow (two - phase FAC). It is reported to be the only mechanism that has significant potential for large leaks in the secondary circuit.

2.0 Mechanism of FAC

The mechanism of FAC is schematically illustrated in Fig. 1 [8]. The iron reacts with water to form a surface oxide layer. This oxide dissolves in the water to form Fe^{+2} and the rate of iron removal (the FAC rate) is controlled by the rate of diffusion of dissolved iron species through the boundary layer of water near the surface into the bulk water. $FeOH^{+}$ is the hydrolysed Fe^{+2} species in solution. This diffusion (or mass transport of iron away from the surface) depends directly on the concentration of soluble iron species at the oxide surface and inversely on the thickness of the boundary layer. Thus, a decrease of the boundary layer thickness because of increased water flow rate or because of local turbulence causes an increase of corrosion rate thus increasing the FAC rate [8]. The main electrochemical steps leading to FAC are listed below:

Steps Involved in FAC

- **Fe (metal) $\longrightarrow$ Fe^{+2} (Oxide-metal interface)**
- **Fe^{+2} (Oxide) diffuses through oxide to water interface**
- **Fe^{+2} (oxide-water interface) $\longrightarrow$ $FeOH^{+}$(dissolved in boundary layer)**
- **$FeOH^{+}$ (dissolved) diffuses through boundary layer to bulk water**
- **$FeOH^{+}$ may get carried away by bulk water**
- **$FeOH^{+}$ (Bulk water) $\longrightarrow$ Fe_2O_3 (Particles, suspended in flowing water)**

A second effect of flow velocity is related to the solubility limit of the dissolving ionic species in the process water. Process water of a given specific chemistry has a definite solubility limit for ionic species at the given (operating) pH and temperature. Once the dissolving ions reach the bulk solution (through the boundary layer) and approach the solubility limit, further dissolution is reduced (e.g. in a stagnant solution). This is where the flow acceleration of corrosion rate takes place. The flow velocity provides a fresh solution (process water) to the metal surface that has a large capacity to take in the soluble ions (as it is far below its solubility limit value) thereby increasing the corrosion rate with velocity. Therefore, FAC is mainly governed by the flow velocity/turbulence affecting the boundary layer on the inside of the pipeline/component and also by the solubility limit of the dissolving ions at the operating parameters.

There have been a few attempts to correlate electrochemical potential (ECP) with FAC rates [10]. One study [10] measured experimentally FAC rates at 140 °C in neutral water and ECP and dissolved oxygen levels and reported that under low oxygen levels, ECP decreased with increase in flow velocity and correspondingly FAC increased. Increased flow velocity was proposed to have lead to decreased boundary layer thickness and therefore to an increasing limiting current density of cathodic reactions. It also leads to increased anodic current density due to decreased protectiveness of inner layer. It was shown from Evans diagram that the ECP (obtained from cathodic and anodic current densities) decreased with flow velocity.

2.1 FAC in Primary Circuit of Nuclear Power Plant

The primary circuit of Pressurized Heavy Water Reactors (PHWR) contains heavy water with pH adjusted in the range of 9.5 to 10.5, by addition of Lithium hydroxide, to minimize corrosion and keep the corrosion products in soluble form (thus preventing activity buildup). Hydrogen addition is also done to suppress radiolytic oxygen production and the temperature in the primary circuit is in the range of 270 – 297 °C in 220 MWe PHWRs. Magnetite solubility (or indirectly the FAC rate) is dependent upon the temperature and the pH [9,13, 14]. Solubility of magnetite which is directly proportional to the FAC rate reduces with increase in temperature below a pH of 9.8. Above a pH of 9.8 the solubility of magnetite increases with temperature resulting in higher dissolution of magnetite (therefore, a higher FAC rate). There is an inversion in the temperature dependence of solubility at the pH range of 9.8-10.3. High pH is beneficial in retarding FAC rate at lower temperatures but at higher temperatures, pH higher than 9.8 results in greater dissolution of the magnetite itself. In the primary circuit of the nuclear power plants the pH and temperature combination results in greater dissolution of magnetite resulting in a higher FAC rate. Examples of FAC degradation of carbon steel feeders have been reported from the primary circuit of pressurized heavy water reactors [9,14].

2.2 FAC in Secondary Circuit of Nuclear Power Plant

The secondary circuit of PHWR contains the process water and the operating temperature is in the range of 150 – 170 °C. The pH in the secondary circuit is adjusted by addition of ethanolamine to obtain a pH in the range of 8.8-9.3. The temperature dependence of FAC rate of various structural materials used in the secondary circuit has been established [15]. It has been shown that the FAC rate in carbon steel and low alloy steels peaks at around 150 °C at pH 7 (which is the temperature of operation in the secondary circuit). The FAC rate also increases in these conditions with increase in flow velocity. Similarly, the effect of flow velocity on the FAC rate at different temperatures for plain carbon steel has been measured and reported [16]. It has been shown that the increase in flow velocity increases FAC rate and the peak in the FAC rate appears in the temperature range of 140-160°C. It has been shown [15-16] that the FAC rate in the secondary circuit can be reduced to a much greater extent at this temperature by increase in the pH to upto 9.8. However, increasing the pH beyond 9.8 at this temperature range would not yield any substantial additional benefit. Other laboratory/plant data also confirm this finding [1-11, 15-17]. Therefore, the secondary circuit components operate at conditions favourable for FAC.

The temperature effect on the FAC rate is actually not direct but the “bell” shaped dependence of the FAC rate on the temperature (Fig. 2) is due to two counter active processes [17]. With increase in the temperature the ferrous ion concentration or the solubility of the ions decreases. At lower temperatures the capacity of water to remove ferrous ions is thus high. But at the same time at lower temperatures the flow viscosity and the ferrous ion diffusivity, which affects mass transfer (in the boundary layer), is lower. These two effects are competing in nature and result in a bell shaped curve (Fig. 2). If the conditions favour large mass transfer such as in the case of high flow velocity, then the thinning kinetics can be very fast even at low temperatures.

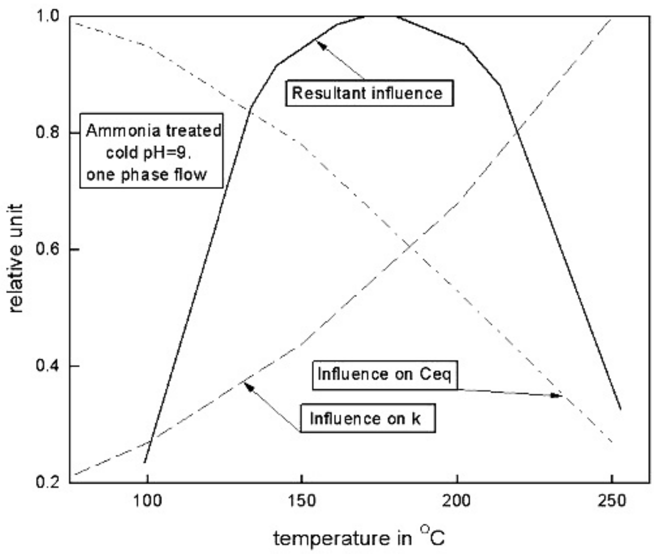


Fig. 2 Calculated influence of temperature on the FAC rate [17].

3.0 Single Phase FAC

Thinning of carbon steel components due to dissolution of protective oxide film and the base metal in the process fluid is termed as single phase FAC. The single phase FAC rate depends on factors like hydrodynamic variables – fluid velocity, pipe configuration, roughness of inside surface of pipe, metallurgical variables – chemical composition including weight percentage of chromium, molybdenum, and copper in steel, and environmental variables – coolant temperature, water chemistry including dissolved oxygen, ferrous ion concentration, metallic impurities in water and pH. The hydrodynamic variables affect the mass transfer and thus affects FAC rate. At low fluid velocity the FAC rate is controlled by the mass transfer while at higher flow velocities mass transfer rate is higher and the FAC rate is governed by the chemical reactions in the oxide-coolant and metal-oxide interface. The micropits formed by the initial selective attack of the carbon steel microstructure grow until they touch each other thus giving a rough appearance to the surface. The corroded surface on the inside surface of pipelines are characterized by overlapping "horse shoe pits" or "scallops" that give an orange peel appearance. These heavily corroded scallop surfaces (either oxides or the base metal) may dislodge and flow out with the high velocity process fluid, thus adding to the already high metal loss rate. Failures that has occurred due to single phase FAC has been described below [7-8].

3.1 Failure in 10% Feed Water Line in KAPS (Secondary Circuit)

A pipe segment in the 10% feed line, immediately downstream of flow element (orifice meter) ruptured releasing steam in boiler room on February 9, 2006, in Kakrapar Atomic Power Station unit-2 (KAPS # 2). The process details and other specifications of the ruptured pipe segment were: Process fluid - feed water (liquid), operating temp. - 171 °C, design pressure - 72 kg/cm², flow and velocity - 35 m^3 /hr (2.33 m/sec), material - A 106 Grade B, size and thickness - 80 NB (7.62 mm). This pipeline carries 10% of the feed water to the steam generator and the failure occurred after approximately 10 years of operation. Fig. 3 (a) gives the schematic of the failed piece of the pipeline showing the location of the fracture with respect to the welds and the location of the orifice meter used for flow measurement [13]. The failure had occurred on the pipeline side of the weld between the flange reducer and the pipeline and it was all along the circumference but was not at a uniform distance from the weld. The observations clearly indicate that the failure is not in the heat-affected zone (HAZ) due to welding. The fracture surface is at varying distances from the weld (at a distance ranging from 2 to 22 mm). Fracture in the HAZ region would approximately be equidistant from the weld all around unlike what is seen here. There is an orifice meter located in the flange for flow measurement and the fracture is downstream the orifice meter. The inner surface that had undergone FAC shows a distinct pattern. This pattern is much finer in the regions severely affected by FAC while it is quite coarse at other locations as shown in the stereomicroscope image in Fig. 7 (b, c). The thickness of the pipeline had reduced from the original (measured) value of 7.11 mm to a minimum of < 2.5 mm at the location of the failure.

Chemical analysis of chips taken from the failed pipeline was done. Except for silicon content, the chemical composition of the material used corresponds to A 106 Grade B of ASTM. The Cr (wt% - 0.032) and Mo (wt% - 0.001) contents of the material was found to be very low (and are typical of A 106 Grade B) in the pipeline material. The fracture surface was examined under the scanning electron microscope and clear ductile failure was observed with no indication of any cleavage facets indicating an overload failure. Since there was excessive thinning observed at this region, the overload failure is due to the pipeline thickness reducing to a level at which it can not withstand the operating load. Similar observations have been reported earlier [1,6]. XRD analysis was done on two samples. The sample taken from regions far away from the failed regions showed presence of magnetite at the ID surfaces. Haematite was not detected in this sample. The sample from the failed region showed peaks due to base metal only. The absence of magnetite (or any other oxide) confirmed that the oxide (magnetite) was getting dissolved at the regions of failure [7-8]. Thickness of the pipe was mapped by ultrasonic method as well as the surface morphology was recorded using a stereo microscope at 11 equidistant locations along the circumference and at an interval of one inch along the length. The thinning was maximum near the flange (at a distance of 1.5 times diameter – this is considered a thumb rule) and it gradually reduced away from it but the reduction in thickness had occurred over a long distance [7-8]. The size of the scallops also changed depending on the extent of degradation. At regions near the fractured regions the size of scallops was smaller as compared to the size of scallops in regions far away from the failed region.

Based on this investigation of this failure, a periodic inspection program for UT thickness measurements of components which are most vulnerable to FAC pertaining to high energy systems of secondary cycle has been prepared and issued for all stations/projects. Decision was also taken to replace the existing carbon steel pipe and fittings of the systems/portion of piping which are prone for FAC with low alloy steel A 333 Gr. 6 (Cr: 0.25-040%). ASTM, A-335 Gr. P22 (2¼% Cr, 1% Mo) [18] could also be a possible choice. Studies have shown [14] that for feeders operating at ~ 310°C, the increased chromium content (to the permissible limit in A106 Gr. B itself) results in a 50% reduction in the FAC rates. For A106 carbon steel, there is an allowable range in specified chromium content of upto 0.4%, and thus increased FAC resistance can be obtained within the A106 Gr. B specification [14]. It has been decided to use of pipes and fittings of one schedule higher than required schedule for FAC prone areas and to analyze and systematically study FAC phenomena from the cut and removed (degraded) pipes and fittings from the secondary cycle piping**.** Results from some such analysis are given in this paper. The layout of piping system and its configuration is also understood to be a contributing factor for FAC. Efforts are being made to study these aspects in existing stations. In the future projects special efforts shall be made to design the piping system layout so as to minimize turbulent flow, direct pipe wall impingement, vortex flows which are the perceptible causes to increase FAC.

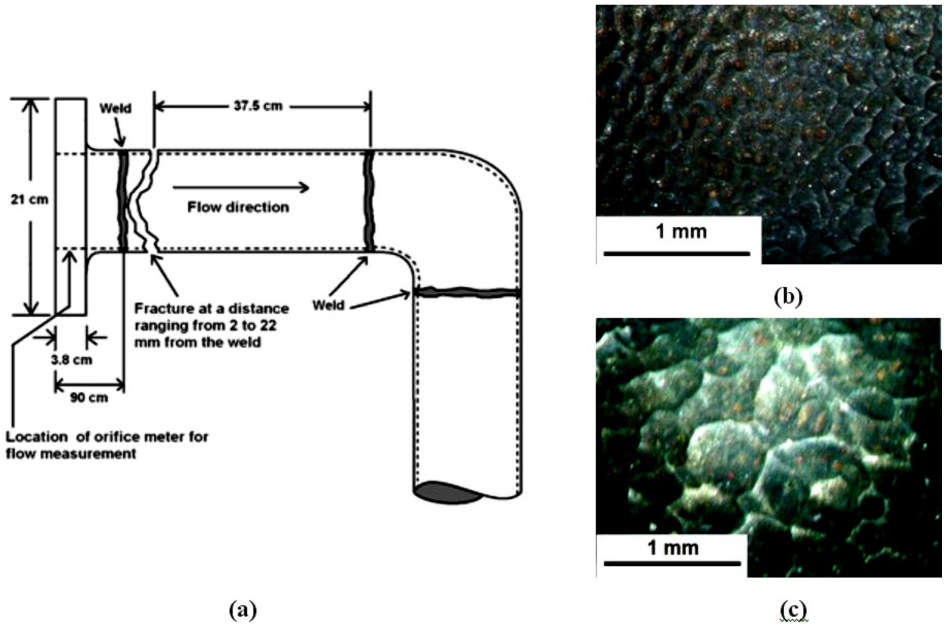


Fig. 3 (a) Schematic of the failed pipeline indicating the location of the fracture surface, welds and the orifice meter for flow measurement. Typical patterns on the ID surfaces as observed by stereomicroscope [7], (b) showing fine pattern near the fracture surfaces (at locations most affected by FAC) [7] and (c) a much coarser pattern at a location that is least affected by FAC [7].

3.2 Failure in Downstream of NRV – 1103 in Auxiliary Feed Water System (Secondary Circuit) of KAPS

The NRV in Auxiliary Feed Water System operates at the following parameters: ~ 150 °C, DO < 5 ppb, pH: 9.5, hydrazine is added for DO control. A leak was noticed at the toe of the downstream socket weld of NRV in the Auxiliary Feed Water System. The pipe was 40 NB size and material of construction was A106 Gr. B. The preliminary visual observation revealed absence of any form of the corrosion on the OD side. A leaky point was easily identified at the interface of the weld with the downstream pipe. A smaller piece was cut through the NRV portion, which contained the leaky region, to facilitate the visual observation on the ID side.

The microstructure of the pipe and NRV portion was ferrite + pearlite, typical of carbon-steel A106 Gr. B. The ID side of the downstream pipe showed substantial degradation. The ID surface was severely corroded. The 40 NB downstream pipe above the weld region, towards NRV side, was severely corroded and in some regions had totally dissolved. It corresponds to Regions C6 - C8 in Fig. 4. Substantial thickness reduction was observed on the pipe portion and thickness reduction was very large near the socket weld (Region C8). Some portion of the downstream pipe had totally corroded, as indicated in Fig. 4 at Region C8 & Region B8 to a distance of 15 mm above it. The socket weld was also affected by corrosion (indicated by surface pattern observed on all the affected regions). A region near the leak (at the downstream pipeline) that showed maximum thickness reduction had shown surface appearance typical of the FAC affected surface patterns and is shown in Fig. 5. It is corresponding to Region A8 in the Fig.4 [8,17].

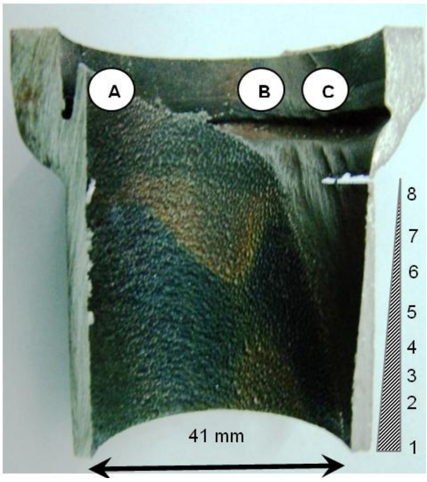
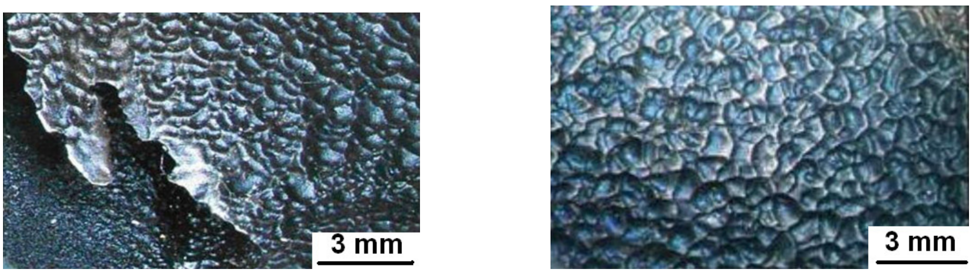


Fig. 4 Heavy thickness reduction near the socket weld (at location 8). Lower thickness reduction is seen at a distance 40 mm away from the socket weld (location 1) [8,17].

Thickness measurements were carried out at different locations in the region where the maximum thickness reduction was noticed. A maximum thickness reduction was noticed in the region where a leak was detected (at location C8 in Fig.9). At the NRV location the geometry of the downstream pipeline (especially the part above the socket weld location) or the returning water stream created very high local velocity regions. This led to FAC to such an extent that a part of the downstream pipe had totally dissolved (Fig. 4). This lead to development of a perforation as the FAC rate on the weld was not as high as on the base material, leading to leakage from the socket weld region. The thickness had decreased to 0.78 mm at location C8 (Fig. 4) from 3.82 mm at location C1 (Fig. 4). Signature surface patterns of single phase FAC were observed at these surfaces (Fig. 5) [17].

Changes in design of the weld, especially its geometry and protruding part after the socket weld of the downstream pipe has to be improved upon to reduce FAC. The use of a better material (containing > 0.3 % Cr or Cr-Mo type steel – e.g. ASTM A333 P22) was also identified as helpful to increase the resistance to FAC.



(a) **(b)**

Fig. 5 a) Surface pattern typical of the FAC at the location most affected by corrosion (Downstream pipeline, C8 in Fig. 10), b) A typical FAC pattern in the region of downstream pipe, corresponding to Region A in Fig. 10 [8,17].

3.3 Failure in Feeder Pipeline in RAPS (Primary Circuit)

Presence of water droplets in the vicinity lead to a discovery of beginning of a small perforation in the feeder pipe B-12 (S) of RAPS-2 in 2007. There was a pinhole developed in the feeder pipe. The material was of ASTM A-106 Grade-B, seamless cold drawn and process annealed. The pipe material showed presence of the magnetite layer characterized by the typical black appearance on the inside surface but the appearance of the magnetite layer was different around the perforation. The inside surface also showed evidences of FAC characterized by typical cellular "scallop" like features on the surface. There was a perforation of ~0.3 mm size adjacent to the weld where the FAC was found to be the most severe. The surface appearance ranged from smooth to pitted, but a distinctive wave-like appearance with smooth scallops and sharp crests was generally prevalent in the areas of more severe damage, especially near the perforation adjacent to the weld. There were two furrow like regions, which had the perforation at one end near the weld. The region of high thinning of the tube due to deeper surface removal was on the leading side of flow beyond the weld region and was characteristic of FAC.

A general loss in the wall thickness of the pipe (along the contour length) was observed during the investigation. Portions of the weld root were seen to be protruding into the pipe at localised regions. The perforation was observed close to one such protruded region. The thickness of the weld was around 3.5 mm at this location while the wall thickness of the pipe was in general around 2.5 mm. It is also observed that at some portions the wall thickness of the pipe near the second weld down stream of flow was less than 2 mm indicating that down stream of the weld joint is more susceptible to FAC [9].

The surface protrusion seen on the inside surface at the weld was due to the root pass of the weld. Due to this protrusion, localized turbulent regions were formed downstream of the weld. The temperature in the primary circuit is higher (around 297 °C) and the higher level of pH (above 10) caused greater dissolution of the magnetite (the solubility of magnetite being higher at higher temperature and pH – see figure 2) causing wall thinning leading to perforation of the tube. The local spot, downstream of the weld protrusion had a much higher velocity and therefore, a much higher FAC rate (the flow rate effect). It is to be noted that magnetite was still present close to the perforation regions. This is due to the fact that the operating temperature here is quite high, leading to quick reformation of the magnetite. However, the signature scallop pattern was observed in both the FAC related failures in the primary and the secondary circuit. These materials are prone to FAC degradation and material selection for future reactors will be based on the operational experience from reactors. The advanced CANDU reactor feeders will be fabricated [14] from type 316LN stainless steel or alloy 800 as these materials have inherent resistance to FAC. These will be fabricated and installed using methods designed to reduce cold work or highly stressed conditions to rule out any possibility of stress corrosion cracking [14]. Balancing water chemistry to reduce feeder pipe corrosion on the primary side requires chemistry to be reducing and controlled to a pH which minimizes dissolution of iron (minimum in magnetite solubility, thus lower FAC rate). This has led to the CANDU primary circuit pH specification being 10.2–10.8, although recently it is suggested that the range of 10.0–10.4 is preferable to minimize feeder FAC [14].

4.0 Dual Phase FAC

The oxide dissolution mechanism is similar to single phase FAC but this kind of degradation occurs in pipes carrying wet steam. Moisture in the steam is essential for oxide dissolution (by electrochemical reactions) and this degradation does not occur in dry steam. The FAC rate varies with the quality of steam that is the amount of moisture in steam. The droplet wear mechanism has been proposed to explain the dual phase FAC [3]. The liquid phase in a steam line flows in a thin layer near the wall while the vapour forms in the core of the flow and moves much faster than the liquid phase. The velocity difference creates shear forces at the liquid vapour interface. If this force is greater than the surface tension force at the interface some liquid will be sheared off the liquid layer and carried over with the vapour. This liquid will form droplets and will be entrapped and accelerated in the vapour core. A fraction of this liquid will impinge on the oxide film on the inside surface and can crack the oxide film thus exposing underlying layers to corrosive attack of the coolant. Surfaces exposed to this kind of dual phase attack have a "tiger striping" appearance [3]. These forms of FAC related ruptures occur not only in the secondary systems of PHWR's but in two-phase systems in some PWR's also [3]. Laboratory tests on dual phase FAC in type 316L stainless steel have also been reported and the test results had indicated very low (negligible) FAC rates in stainless steel [20]. Stainless steels have high resistance to FAC related degradation. The FAC kinetics is slow in stainless steels.

A variant of "dual phase FAC" is the liquid droplet impingement (LDI) [21]. The Fig. 6 shows [21] the conditions that cause single and two versions of dual phase FAC. LDI is also sometime referred to as shotgun pattern corrosion. LDI is also divided into two types: one is determined by mechanical process (designated as LDI (mechanical) is dominated by the flow dynamics (physical and mechanical) process and the other is determined by corrosion (chemical) process (designated as LDI (corrosion)).

LDI on the turbine blades is a typical pattern of LDI (mechanical), which is often mitigated by improving surface hardness, *e.g.*, application of stellite alloy coating. Air vent lines of feed water heaters are often damaged by LDI, which shows a typical pattern of LDI (mechanical) for high velocity steam and a typical pattern of LDI (corrosion) for low velocity steam. In the case of LDI in air vent lines, even if there are small holes, lower pressure in the piping than ambient one results in in-leakage but not out-leakage, which does not cause serious environmental damage, nonetheless results in leakages.

The LDI is further illustrated [21] by showing that the liquid droplets carried in steam directly impinge on the wall of the elbow and at that location liquid droplet impingement happens. This is possible when the droplets reach at a very high velocity (otherwise at slow velocity the normal FAC would occur). If the droplets reach at medium velocity, the oxide film would get ruptured, exposing the underlying bare material and enhancing the corrosive mechanism of LDI. It should be noted that the single phase FAC rate does increase with increase in flow velocity but after a certain velocity of the process stream, the FAC rate does not vary. However, the thinning rate goes on increasing with steam velocity in case of LDI. The dependence of the velocity on LDI (and FAC) rates is shown in Fig. 7 [21]. It can be seen that LDI starts with velocities of around 200 m/second and the thinning rate varies with the diameter and density of water droplets in steam. The LDI thinning rates are much higher compared to those from FAC.

Liquid droplet impingement has been reported at nuclear and fossil power plants [22]. Especially at air vent lines of feed water heaters of BWRs, liquid droplets included in high speed steam flow collide with the inner surfaces of sharp bends in piping.

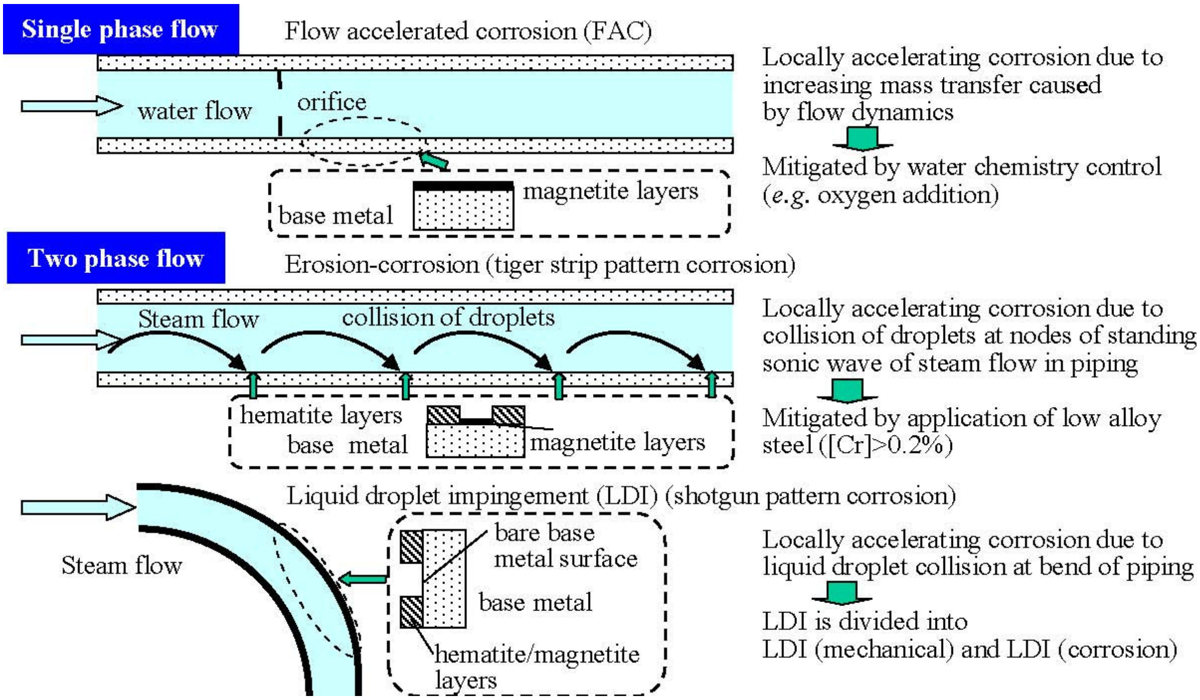


Fig. 6 Flow accelerated corrosion: Single phase and dual phase thinning and the conditions causing the thinning [19].

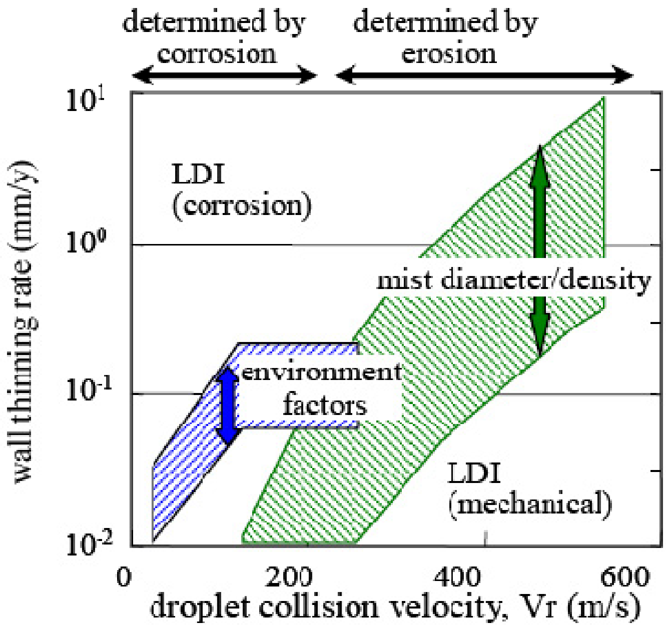


Fig. 7 Regimes of LDI (mechanical) and LDI (corrosion) [19].

4.1 Other Cases of FAC Thinning from Examination of Affected Components from Secondary Circuit of PHWRs

The examination of other components affected by FAC in Indian PHWRs (secondary circuit) is being regularly done and some studies have been reported [7-9, 21-22]. The cases of thinning/perforation in a 60" diameter (9.53 mm thickness) HP turbine exhaust steam line to moisture separator that had developed two pinholes [8, 23] and (b) the components examined from secondary feed water system, main steam system, and the reheater drain system of KGS 2 have been described in detail elsewhere [8, 24]. These case studies illustrate the typical FAC signature patterns confirming occurrence of FAC.

4.2 FAC vs. Mechanical Thinning

A few cases of thinned components from secondary circuit were established where thinning had not occurred due to FAC but had occurred due to other mechanical means. One example is from a 65NB 45° elbow and straight pipe sections on either side of the elbow from the feed water system from the secondary side of TAPS-4 that had been replaced as thinning had been measured. The extrados region of the elbow had thinned down considerably [8, 25]. The internal surface of the elbow was seen to be very rough and there was considerable loss of wall thickness at the extrados. At one point the wall thickness had reduced to 0.71 mm. The thickness measured at the intrados was 6.46 mm. Thinning of the elbow had also extended in to the straight section of the pipe to some extent. The elbow was cut open and the internal surface was observed using a stereo microscope. While signature patterns of FAC were not observed at the affected regions, formation of grooves could be observed. In the regions of extensive localized thinning/grooving the direction of the grooves was in the flow direction. 'This was attributed to be due to "flashing". Flashing' of high pressure high temperature water leading to formation of steam is expected in this region.

Another example refers to (1) Pipe piece from Extraction-6 drain line and (2) Elbow that was being used at turbine stage II drain of HP turbine of KAPS 2 [8, 26]. It was in operating condition in the secondary system until thickness measurement obtained with the help of ultrasonic testing in the plant showed that it had got degraded in thickness and its residual life was lowered. The operating parameters were: (1) Temperature –around 200 °C, (2) Operating Pressure-40 Kg/cm^2 and (3) Water Chemistry: a. Deoxygenated water and b. pH was 8.8 to 9.5 maintained with the help of amines (ETA). The chemical analysis and the optical micrographs of the materials showed it to be a low carbon steel. XRD analysis on the ID side of the samples showed the presence of magnetite as well as that of haematite. Stereomicroscopy was done however due to a dark black layer of oxide the surface features were not clear. From the images no specific pattern could be observed. Scanning electron microscopy of the sample which was taken from the region of maximum thinning was done to reveal surface morphology so as to see if there are any sign of FAC (scallops). Signature appearance of FAC was absent indicating there cannot be FAC. Also at higher magnification we find that there are some signs of erosion corrosion. On examination of the images at higher magnification it is indicated that some material has been removed by impact of particle (of few microns). It is inferred that this particular case is not directly attributable to FAC as no distinct signature of FAC was observed on the affected surfaces. The observations indicated towards erosion corrosion taking place in the system that is clear from SEM examination of the affected surfaces that show impingement/erosion features.

5.0 Control Measures against FAC

UT Thickness Monitoring Program in Indian Plants

Periodic inspection program for UT thickness measurements of components which are most vulnerable to FAC pertaining to high energy systems of secondary cycle has been prepared and issued for all stations/projects. Subsequently scope of examination was enhanced by recommending to stations for monitoring all the potential locations of high energy secondary cycle piping to develop base line data.

Replacement of Affected Carbon Steel Material

Decision was initially taken to replace the severely degraded carbon steel pipe and fittings of the systems/portion of piping on a trial basis with low alloy steel ASTM, A-335 Gr. P22 (2¼% Cr, 1% Mo) [7, 18] in the secondary circuit and to observe their performance. The FAC rates for a 90^0 elbow predict that FAC rate reduces to one tenth of the FAC rates for a carbon steel pipeline when Cr content is increased from 0.03% to 0.5%. A better grade of carbon steel (ASTM A 335 Grade 11/22) has been used in many plants with much better resistance to FAC. The surface oxide changes from Fe_3O_4 to $FeCr_2O_4$ with addition of Cr in carbon steel. In view of the above, another important aspect is to establish is replacement with the same grade A 106, grade B (but containing 0.25 – 0.40% Cr) would be effective. Such components are currently being used at sections which are more prone to FAC degradation.

Stainless steel and alloy steel were found to be possible alternate replacement materials for carbon steel as these are significantly less susceptible to FAC (with SS grade 316L being the most suitable material). But the substitution with austenitic stainless steels will require some additional engineering aspects. These materials have a thermal expansion rate, which averages 1.4 times greater than plain carbon steel. Susceptibility to chlorides stress corrosion of austenitic grade is another concern related with the chloride contaminants in thermal insulation. The replacement with SS was initially considered (for feeders in PHT of PHWRs) in some advanced reactors (under design) but has not been implemented yet. Current consideration is focusing on evaluating the choice of alloy 800 for feeders.

Provision of Increased Corrosion Allowance

It has been decided to use pipes & fittings of one schedule higher than required schedule for FAC prone areas.

Analysis of Cut and Removed Components

It has been decided to analyze and systematically study FAC phenomena from the cut and removed (degraded) pipes and fittings from the secondary cycle piping. Some examples from these plant removed components (from secondary circuit) have been provided in this paper.

Water Chemistry Changes

The pH of the feedwater has a strong influence on the FAC rates. As the pH is increased beyond 9.0, the FAC rates decrease upto 10.0 at the operating conditions. It has also been shown that the maxima in FAC rates appear at a pH of 9.5. Therefore, a raise in pH to close to 9.5 - 10.0 would help reduce the FAC drastically. However, caution has to be taken to consider the effect of this rise in pH on corrosion of other components. Especially that of any copper based alloys, the corrosion of which increases with rise in pH. Also the influence of this rise in pH has to be assessed for its possible influence on corrosion and cracking of SG tubing from the secondary side.

The Chexal-Horowitz model predicts the FAC rates to drop from 3.2 to 0.89 mm/year as the dissolved oxygen content is increased from 10 to 30 ppb. The effect of DO level is related to the formation of haematite in preference to magnetite on carbon steel surfaces when the DO levels are high. The rate of dissolution of haematite is slower than that of magnetite in the feed water hence the drop in FAC rates. It has been reported that in the secondary circuits of PWR, an injection of oxygen to obtain around 10 ppb is sufficient to achieve reduction in FAC rates. However, before any increase in DO levels in the secondary circuit to control FAC rates, its effect on (i) long term corrosion performance of SG tubing (especially corrosion of Monel 400 tubing and cracking of alloy 800 tubing) and (ii) any possibility of increase in crud levels has to be assessed.

Design Improvements

The layout of piping system and its configuration is also understood to be a contributing factor for FAC. The efforts are being made to study these aspects in existing stations. However it is felt that changing the existing layout will be difficult. In the future projects special efforts shall be made to design the piping system layout so as to minimize turbulent flow, direct pipe wall impingement, vortex flows which are the perceptible causes to increase FAC. The local flow velocities are important (e.g. downstream of flow disturbance). This is due to the turbulent (as against laminar) flow that is generated just after passing the flow-measuring device/flow restriction/change of flow direction forming a complex velocity pattern. These can be two to three times the bulk velocities. For most feed water segments, modeling has shown that the maximum FAC rates are at the temperature of ~ 150^0C.

Future Plans

The computer soft-wares / codes analyze and predict the susceptible FAC components and locations so that FAC management can be done on such locations in a more effective manner. Efforts will be made to develop with other R&D organizations such a soft ware.

6.0 Conclusions

A number of FAC related degradations have occurred in both the primary and the secondary circuit of nuclear power plants. Single phase FAC has been reported in the feeder pipelines in the primary side of PHWR's and both single phase and dual phase FAC have been reported in the secondary side of the Indian nuclear power plants. FAC rates depend on the solubility of the surface oxide which shows an inversion in the temperature dependence in the pH range of 9.8-10.3. Signature patterns form on the surface of the components undergoing FAC degradation. Clear "horse shoe or scallop" patterns are visible on the surface of components undergoing single phase FAC in both the primary and the secondary circuit. "Tiger striping" like patterns are visible on the surfaces exposed to dual phase FAC in the secondary circuit. Components where FAC degradation has just initiated showed that the patterns are not well defined. The signature patterns become evident only after the degradation has occurred to a large extent. FAC like features have been seen in stainless steel components also in the secondary side. However, thinning was largely attributed to fabrication and not to FAC. No FAC related failure/thinning in stainless steel components have been reported as these are inherently not prone to FAC. This paper describes the mechanisms of single and dual phase FAC and contrasts it with liquid droplet impingement (LDI). The analysis of components affected by FAC (from Indian nuclear power plants) has been described to illustrate the extent of FAC and the typical signature patterns to establish single or dual phase FAC. Two case studies have been reported in this paper that describe that the typical surface patterns of single/double phase FAC were not observed on the affected surfaces. In one case, the degradation is attributed to flashing and in the other case to erosion. Therefore, examination of thinning (and removed from service) components from service provides valuable information and establishes type and extent of FAC/degradation.

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