B. 17 "Flow-Accelerated Corrosion,"
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Background

Flow-accelerated corrosion (FAC, sometimes termed flow-assisted corrosion) is a degradation mechanism affecting metallic materials that do not form tightly adherent passive surface films when the materials are exposed to fluid flow environments in power reactor systems, and thermal power plants. In reactor coolant/heat transfer systems where materials are exposed to flowing water this degradation mechanism typically affects only carbon steels and copper alloys. Sometimes the FAC results in sufficient wall loss that catastrophic piping failure occurs (Figure B.17.1), although more frequently leakage is the consequence, without rupture. It is important to note the distinction between FAC and erosion corrosion (EC). FAC is an electrochemical corrosion process dependent on pH, temperature, electrochemical potential and fluid mass transfer (velocity and turbulence). FAC is a flow-accelerated increase in the corrosion rate of a material; the increase in corrosion rate, which can be very large, can be simplistically thought of as a flow-induced increase in mass transfer of dissolving and reacting (corrosive) species at a high flow or highly turbulent location. Under low flow conditions, the corrosion rate of carbon steel is an electrochemically-coupled reaction and is a function of the rate of dissolution of the substrate (Fe for carbon steels) and the oxide formed by reaction of some of the dissolved iron with water and water-borne oxidants, and the rate of formation of a surface oxide. Under FAC conditions the rate of Fe/ iron oxide dissolution exceeds the rate of formation of the oxide that would be expected under low flow conditions. This coupled oxidation/dissolution reaction is best described as an electrochemical process, determined by the concentration of electrochemically active species at the metal-fluid interface, in particular those controlling the pH and oxidants.

Erosion corrosion is properly described as the abrasive or cavitation-induced (mechanical) removal of surface material; either the protective film or the underlying material for systems that do not form protective surface layers. A common form of EC in LWRs is related to entrainment of abrasive material in a fluid flow, for instance sand entrainment in water intake flows, and both FAC and EC may occur simultaneously, depending on the flow conditions. Typically, power plant cooling and heat transfer systems do not contain abrasive materials in quantities sufficient to cause EC, although condenser cooling water systems may contain abrasive debris. Under very high flow conditions, best described as water jetting or steam jetting, the abrasive wear or cutting of the material can take place without abrasive materials being present. Typical examples are steam cutting/wear in condenser inlets and the use of high pressure (typically 5000 to 10 000 psi) water lances to cut concrete. It should be noted that the term "erosion-corrosion" has been frequently used as a synonym for FAC, which can be confusing and is incorrect.

Factors Influencing Material Susceptibility

There are several factors affecting susceptibility to FAC:

- pH
- Temperature
- Water chemistry
- Material properties (alloy content)
- Mass transfer (flow, turbulence, steam quality)

For carbon steels, the pH should be controlled in the range 7 to 10, preferably between 9 and 10 (room temperature pH) to minimize corrosion in water. For copper alloys the pH should be between 7 and 9; thus in mixed metal systems pH control is a compromise between corrosion of carbon steels and copper alloys, and pH is typically in the range 8.8 to 9.4. Most nuclear plants have now switched to all-ferrous piping systems, primarily to protect steam generators from degradation, and thus there is little concern for corrosion of copper alloys. In all-ferrous systems the pH is typically maintained >9.4, often as high as 9.8 to 10.0. Note that in two-phase systems, such as in steam generators, it is the liquid phase pH that is important and pH control agents should be chosen such that preferential partitioning to the steam phase does not occur, or does not lower the liquid phase pH below an acceptable level. So-called “alternative amines” have been used to ensure that such partitioning is limited and thus the high temperature pH of the liquid phase remains in an acceptable range.

Water temperature significantly affects FAC, with the maximum FAC rates occurring, all else being equal, at about 130°C in single-phase flow, and at about 180°C in two-phase flow. Thus the feedwater systems are at significant risk of FAC, and these systems are typically inspected on a routine basis to ensure that wall thinning is monitored. FAC in these systems can result in wall loss rates of >10 mm/year in unfavorable situations, and in a few cases has resulted in deaths as a consequence of pipe rupture when the wall thickness decreased sufficiently that mechanical failure occurred. Typically FAC rates decrease at temperatures on either side of the peak temperature, all other factors being equal, but given that FAC is often very localized because of mass transfer effects, the rate may still be sufficient to result in wall thinning and piping failure in thin-walled pipes.

Water chemistry is an important variable for FAC. The conditions leading to increased FAC rates are reducing chemistry (low electrochemical potential) and low dissolved iron concentrations in the water. Steam generators are an example of how FAC can occur under the highly reducing conditions that are typically used to protect the SG tube bundle. In several instances (Bruce NGS and Gravelines, for example) carbon steel support plates have disintegrated as a consequence of FAC, where it was concluded that a significant factor was the use of high hydrazine concentrations (>100 to 200 ppb). The sensitivity of FAC to low dissolved iron concentrations is a consequence of the dependence of FAC on the solubility of iron, and to the local potential. In fundamental terms this dependence relates to the liquid layer at the steel surface, which becomes more difficult to measure and predict in two-phase flows. In feedwater systems this iron solubility dependence is most obvious in systems such as the moisture separator reheater drain lines, where steam has been condensed and relatively iron-free water is flowing. Many cases of FAC have occurred in such lines. Note also the use of alternative amines to ensure appropriate high temperature pH in two-phase flows (see Secondary Water Chemistry Topical Report) also mitigates these effects of iron concentration and potential on FAC.

Material properties have a significant impact on FAC rates, and typically the plant operator has no control over this unless replacement of piping is an option. The most important alloy variable affecting FAC is chromium (Cr) content of the alloy. Although copper and molybdenum content have also been suggested to have beneficial effects, the effects are typically small and not clearly related to plant experience. It is generally regarded that in single phase piping subject to FAC, a Cr content >0.1 wt. % is recommended. Plant and laboratory data suggest that Cr contents below about 0.04 wt. % are insufficient to provide any useful protection against FAC, and concentrations above 0.05 to 0.08 wt. % are necessary to show significant improvement. Many experts now recommend a Cr content >0.2 wt. % to provide optimal resistance. The beneficial effect of Cr on FAC is thought to be related to the formation of a Cr-rich oxide at the oxide-metal interface, and that this oxide confers resistance to FAC. In two-phase flows, which are typically very much higher velocity than single phase flows, it is probably expedient to use Cr-Mo steels or, preferably, stainless steels. Many feedwater system components are now fabricated from these materials to minimize FAC degradation.

Mass transfer effects relate to areas where locally high turbulence is created, usually by geometric factors. Elbows, bends, orifices, valves, etc., all cause local turbulence which significantly increases FAC rates in or immediately downstream of the component. This turbulence increases the FAC rate by increasing the transport of dissolving iron away from the surface and, by increasing mechanical stresses on the oxides formed at the site of the corrosion, which can be significant under very high velocities.

Typical Occurrences of FAC in Power Plants

Most of the FAC degradation in power plants has occurred in feedwater, extraction steam, and drains systems. However, there have been observations of FAC in steam generators and in primary side piping in CANDU™ (Canadian Deuterium Uranium) PHWR (Pressurized Heavy Water Reactor) power plants. In these systems, FAC has been found in most parts of the system, and is often associated with areas of high mass transfer, such as downstream of welds and valves, reducers, orifices, and in elbows and tees. The SG FAC has been typically found in two-phase flow areas, including upper support plates, steam separators and blowdown piping. In the CANDU heat transport system (310°C, velocity 15 to 18 m/s), the FAC has occurred at bends in carbon steel outlet feeder piping. The FAC rates there are much lower than in the feedwater and SG systems, but still can impact the integrity of the thin-wall feeder piping.

In condensers, steam impact erosion has occurred on the outer tube bundle where the steam inlets are located, a degradation phenomenon similar to that found in turbines, and has been resolved using stainless steels in this area and changes to the inlet flow distribution. This degradation occurs because the steam, by the time it reaches the condenser, is sufficiently wet that droplet impingement occurs, in addition to FAC (depending on the tube material and its susceptibility to FAC). On the water side of condensers made with copper alloy tubing, in particular Admiralty Brass, significant FAC and erosion occurs, usually resulting in tube leakage and the need to replace the condensers after about 15 years or so.

Inspection and Remediation Strategies

The most effective management strategy for FAC of feedwater systems is to employ a FAC prediction code such as EPRI's CHECWORKS code, or an equivalent, to predict locations most susceptible to FAC, and then to focus inspections on those locations predicted to be most at risk. Without use of this code, or an equivalent, it is difficult to predict and prioritize the many locations that could suffer FAC. Usually the Cr content of the steel is unknown, so it is not possible to restrict inspections to only one train of a given system, regarding it as a "lead" train. It is generally known that all high mass transfer areas are susceptible to FAC, but some may degrade at much slower rates than others, depending on hydraulic and chemistry conditions, and thus an inspection prioritization plan is needed. Note that the recent Mihama-3 pipe failure (see Figure B.17.1), caused by FAC, was in a line predicted by CHECWORKS to be at risk, but never inspected.

For steam generators, visual inspection for internal secondary side carbon steel components is usually necessary; this inspection, based on in-service experience so far, can be limited to upper support plates and separators.

The most effective remediation strategies are to replace all degraded material with stainless steel, or with Cr-Mo material if the post-weld heat treatment requirements are feasible. Typically as feedwater system carbon steel components have failed, replacements have been with FAC-resistant material. For new systems, analysis of the system can identify locations at risk of FAC and these are fabricated from austenitic stainless steels (Qinshan CANDU plants, for example). Some plants have essentially all-stainless steel feedwater systems (KWU Konvoi plants, for example). All new SGs have stainless steel support plates and other internals susceptible to FAC. For condensers, most plants have now replaced any copper-alloy condensers with Ti-tubed units (seawater cooling), with appropriate baffles to prevent inlet steam erosion of the outer row Ti tubing, or with stainless steel units (seawater and freshwater cooling).

Remediation by chemistry modification has limited application given that most plants now employ an effective feedwater chemistry control designed to minimize FAC and other degradation mechanisms. For SGs with carbon steel secondary side internals, reducing hydrazine to <100 ppb is recommended.

Life Management Issues

Current industrial practice is to routinely inspect for FAC-induced wall thinning, usually using a predictive tool such as CHECWORKS in order to minimize the number of critical locations, as well as to generate a database of at-risk locations, the inspection history, and the wall thinning rate. Where piping failures occur, replacement of a failed component should be with a more-resistant material. It is cost-effective to reduce inspection by replacing carbon steel with stainless steel in at-risk areas. Chemistry control should be monitored to ensure that it is compatible with reduced FAC risk; operation of feedwater systems at very low dissolved oxygen (<5 ppb), for instance, can place the system at increased risk compared to slightly higher oxygen (5 to 10 ppb).

Figure B.17.1 Failed steam line at Mihama-3.

References for B.17

[1] B. Chexal et al, "Flow-Accelerated Corrosion in Power Plants," EPRI TR-06611-R1, Electric Power Research Institute, 2001.

[2] "Erosion/Corrosion in Nuclear Plant Steam Piping: Causes and Inspection Program Guidelines", EPRI NP-3944, Electric Power Research Institute, 1985.

[3] I.S.Woolsey, "Erosion-Corrosion in PWR Secondary Circuits," CEGB (Central Electricity Generating Board; UK) Report TPRD/L/3114/R67, 1987.

[4] V.N. Shah and P.E.Macdonald, eds., "Aging and Life Extension of Major Light Water Reactor Components," Elsevier, Amsterdam (1993); ISBN 0 444 89448 9.