Flow-Accelerated Corrosion (FAC) in Conventional Fossil Units: Cycle Chemistry Influences and Management Approach

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ABSTRACT

The authors have reviewed flow-accelerated corrosion (FAC) programs used at various types of conventional fossil plants. The results and findings of the assessments are presented and discussed. A number of emergent areas of FAC damage have been added to the previous suite of recognized susceptible locations with a concentration on damage due to two-phase FAC. Several deficiencies related to feedwater chemistry and FAC management approaches were noted to be common among the plants. These characteristics may influence the FAC susceptibility and awareness at other plants.

INTRODUCTION

A recent publication reviewed the science of flow-accelerated corrosion (FAC) and the industry experience in conventional and combined cycle plants [1]. One of the major points made throughout the review was that FAC has basically been understood for over 30 years and the major influences are well recognized, but that the application of the science and understanding to fossil plants has not been entirely satisfactory. Major failures are still occurring and the locations involved are basically the same as they were in the 1980s and 1990s.

Commonly recognized locations of FAC damage and failure in conventional fossil plants (S: single-phase, T: two-phase) prior to publication of the earlier review [1] included the following:

- Feedwater heater normal drains (S, T). Most prevalent area, where about 60 % of organizations record problems.
- Piping around the boiler feed pump (S). Includes steam attemperation supply piping and downstream spray control valves (S, T).
- Piping to economizer inlet headers (S), especially associated/near valves and supply tees.
- Economizer inlet header tubes (S). Most frequent are usually those nearest to header supply.
- High pressure (HP) feedwater heater tubes and tube sheets fabricated in carbon steel (S).
- Low pressure (LP) feedwater heater shells (T), especially near cascading drain entries.
- Deaerator shells (T) near to fluid entry (HP cascading drains) piping.
- Expanders and reducers on either side of valves (most often T).
- Locations near thermowells in piping (S).
- Turbine exhaust diffuser (T).
- Air-cooled condenser (T).
- Downstream of control valves (most often T).

The work described in the current paper moves on from this review to expand the earlier compilation of damage locations. It confirmed that many recent two-phase FAC incidents have occurred at locations not widely noted by earlier investigations, including alternate drains piping as well as in piping around the boiler feed pump. It provides the practical results of a number of FAC assessments and surveys during 2008 and early 2009 on a number of fossil plant units to determine if there is a better way of recognizing the locations as a function of the interfacial science for the various materials/cycle chemistry combinations now used by the industry.

The recent survey findings show a trend of gradual change from earlier end user reports of mainly observations of single-phase FAC damage to an increased frequency of observation of two-phase damage incidents. This trend seems to indicate increased awareness of the benefits of oxidizing feedwater treatments in arresting single-phase FAC and improved recognition of two-phase damage, which in the past was often misdiagnosed as another mechanism such as cavitation or liquid droplet erosion. Finally, the results identify the continuing weaknesses in organizations' overall FAC programs: particularly in that the cycle chemistry program is rarely fully integrated with FAC control. Because of the importance of FAC failures and the increased levels of corrosion products observable in situations when the cycle chemistry is not optimized (such as following changes in the feedwater heater metallurgy), it appears of paramount importance for organizations to consolidate their inspection, predictive capabilities, and chemistry approaches into a company-wide coordinated FAC program in the same way as many do for boiler tube failure reduction.

PLANT FAC ASSESSMENTS

Over an approximate one year period, the authors have performed FAC program assessments at 13 conventional fossil plants involving 27 units. Interest in program assessments was often driven by local experience, including piping leaks and visual observation of damage suspected to be FAC during unit outages. A further consideration in some instances related to infrequent but continued incidents of serious FAC failures across the industry. A number of assessments were conducted on units where no programs existed or an earlier program had become inactive.

The factors involved in the assessment process are summarized as follows.

1. Plant/unit demographic characteristics:
    - MW capacity;
    - Boiler type and pressure;
    - Mode of operation and number (type) of startups;
    - Feedwater heater and other exchanger/cooler materials in the cycle over the service life of the unit including any tube replacements;
    - Number and arrangement of boiler feed pumps;
    - Heater drain arrangement (normal, bypass, and high level).
2. Discussion and benchmarking of FAC program:
    - Organizational position (Is there a management directive in effect?);
    - Previous evaluation findings for the last 10 years (Has an FAC predictive code been applied?);
    - Previous inspection findings;
    - Known damage/failure events;
    - Repair/replacement practices.
3. Determination of cycle chemistry program attributes and program benchmarking:
    - Feedwater treatments, chemical addition points and control philosophies used over the service life of the unit;
    - Chemistry instrumentation (Are the structural integrity fundamental analyzers installed and alarmed in the control room and to what extent are grab sample analyses utilized?);
    - Operating chemistry results for on-line analyzers (as characterized by screen shots from the control room distributed control system), and comparison to limits and action levels and historical levels;
    - Air in-leakage approach (current and historical values);
    - Total iron and copper (mixed-metallurgy units) testing practices and results.
4. Evaluation of unit operating conditions:
    - Cycle heat balance diagrams;
    - Operations practices (drains operation, venting practices, spray attemperation, boiler feed pump operations, etc.).
5. Investigation of plant piping:
    - Piping and instrumentation drawings;
    - Elevation drawings;
    - Isometric drawings;
    - Piping walk down inspections to identify locations likely to have increased local turbulence due to geometric features and high traffic areas;
    - Review of previous inspection reports and information on any pipe failures in the feedwater system.

OBSERVATIONS

Overall findings of these surveys are presented in a series of tables. Table 1 presents basic demographic information on the plants and units assessed, including unit capacities, boiler types and boiler pressures. It also includes some information on materials employed in feedwater heater tubing and drain piping. Feedwater chemistry attributes of the plants and units are presented in Table 2. Locations of prior FAC damage are summarized in Table 3. Table entries include locations determined by inspection as well as any which developed leaks in service. Table 4 presents a comparison summary of FAC program characteristics and actions for each unit prior to assessment by the authors.

Further details and comments on the plants assessed are presented in ensuing sections of the paper.

DEMOGRAPHICS AND MATERIALS

Overall plant demographics (Table 1) are not considered unusual. The assessment population includes fossil units with supercritical and drum boilers. It includes units commissioned in the 1950s–1980s. Most of the units are normally in service, often subject to load cycling.

As would be expected, the units with once-through boilers had all-ferrous feedwater systems while several of the units with drum boilers had some copper alloy material in the feedwater system. In some of the drum boiler units a change in feedwater heater tube metallurgy (from copper alloys to stainless steel) had been made. Such action generally increases the FAC risk, especially in those instances where the cycle chemistry needs are not reassessed or modified as needed and the optimization is not confirmed.

Units at one of the plants did not include a deaerating heater as part of the cycle design. Heater drain piping in all surveyed plants was primarily carbon steel. However, one design had provided for installation of 2.25 % Cr alloy steel (P22) on drains piping at points where flashing to a two-phase fluid was likely to occur. This unit was constructed in the 1980s suggesting that some foresight had been applied with respect to minimizing two-phase FAC susceptibility. One of the older units had a design in which the distance between heaters was minimized, thereby reducing the number of bends and eliminating sources of increased local turbulence.

FEEDWATER CHEMISTRY AND RELEVANCE TO FAC

Available choices for feedwater treatment (Table 2) include reducing all-volatile treatment, AVT(R), oxidizing all-volatile treatment, AVT(O), and oxygenated treatment, OT. Treatment must be selected consistent with the needs of the unit, based on the materials used in the feedwater system. Cycles with copper (mixed-metallurgy) should employ AVT(R) while those without copper (all-ferrous cycles) should use either AVT(O) or OT. For cycles with once-through boilers, OT is widely accepted and used. All-ferrous cycles with drum boilers generally use AVT(O) though use of OT is also possible when certain criteria can be met. Use of oxidizing chemistries effectively reduces single-phase FAC activity to a very slow rate depending of course on the level of oxygen in the cycle. Use of reducing agents is intended to protect the copper alloys present in cycles with mixed metallurgy. Several reducing agents were used at the various plants with the most prevalent being carbohydrazide. Ammonia was typically added for pH control though some plants used neutralizing amines.

Plant	No. of units assessed and capacity [MW]	Boiler type and pressure [MPa] ([psi])	Feedwater heater and drains metallurgy	
			Condensate pump discharge to boiler feed pump	Boiler feed pump to economizer inlet
A	3 x 660	OTSC	All-ferrous	All-ferrous
B	2 x 125	D – 11.0 (1 600)	All-ferrous	All-ferrous/ Mixed-metallurgy
C	3 x 125	D – 13.8 (2 000)	Originally mixed-metallurgy but present materials could not be confirmed for some heaters	
D	85/167	D – 10.3 (1 500) and D – 14.2 (2 065)	Mixed-metallurgy	Mixed-metallurgy/ All-ferrous
E	2 x 125	D – 8.6 (1 250)	Mixed-metallurgy/ All-ferrous	All-ferrous
F	3 x 500	OTSC	All-ferrous	All-ferrous
G	2 x 550	OTSC	All-ferrous	All-ferrous
H	2 x 490	D – 18.3 (2 650)	All-ferrous	Mixed-metallurgy
I	2 x 700	OTSC	All-ferrous	All-ferrous
J	1 x 300	D – 17.9 (2 600)	All-ferrous	All-ferrous
K	1 x 85	D – 11.4 (1 650)	Mixed-metallurgy	Mixed-metallurgy
L	55/188	D – 9.3 (1 350) and D – 12.8 (1 850)	Mixed-metallurgy	All-ferrous
M	450/630	D – 13.4 (1 950) and OTSC	All-ferrous / All-ferrous	Mixed-metallurgy/ All-ferrous

Table 1:

Demographics (general and FAC-relevant) of assessed plants.

Boiler type:
OTSC: Once-through supercritical steam generator; D: Drum-type boiler

A very common observation amongst the surveyed plants was the ineffectiveness of air removal capabilities. In units where there is a comprehensive air in-leakage control program it should be possible to routinely maintain dissolved oxygen at the condensate pump discharge at or below 10 $\mu g \cdot kg^{-1}$. In a few instances unit deaerating heaters were reported to have experienced problems as well, but these were generally corrected, whereas acceptance of high condensate air in-leakage was more often regarded as a chronic repeat situation [2]. This is especially detrimental in units with mixed-metallurgy, where the reducing conditions produced by optimized AVT(R) treatment are required to minimize copper corrosion. However, it is also of concern in units employing oxygenated treatment (OT) as accumulation of non-condensable gases in feedwater heaters and deaerators necessitates venting and, in fact, sometimes leads to operation with open vents. Frequent or continuous (including partial) venting of units treated with OT is a non-optimal practice. Oxygen is desirable in the liquid phase at areas of drain piping potentially subject to single-phase FAC damage. Ammonia or others amines are needed following flashing to minimize two-phase FAC damage. Optimized OT units are operated with the feedwater heater and deaerator vents completely closed to ensure maximum pH by maintaining higher levels of ammonia or amine in the drain lines; this is most readily accomplished when air in-leakage is well controlled.

An important aspect of FAC susceptibility assessment in conventional fossil plants concerns the color of carbon

Plant	Feedwater treatment / pH	Chemical usage summary			Dissolved oxygen [$\mu g \cdot kg^{-1}$]		Fundamental chemistry analyzers [%]	Iron transport [$\mu g \cdot kg^{-1}$]	
		pH control agent	Oxidizing/ reducing agent	Feed point	CPD	EI		EI	Heater drains
A	OT / 8.85–9.3	Ammonia (based on SC)	Oxygen	CPD and DAO	< 75	75	64	---/ (10 years)	---
B	AVT(R) / 8.8–9.2	Ammonia	Carbo-hydrazide	CPD	< 6	1–5	87/100	10–30	---
C	AVT(R) / 8.9–9.1	Cyclo-hexylamine	Carbo-hydrazide	BFPS/ CPD	20	< 5	53 /73/73	< 9	---
D	AVT(R) / 8.8–9.2	Cyclo-hexylamine	Hydro-quinone	CPI, CPO, LPFWHI	5–20	< 5	53	---	---
E	AVT(O) / 7.5–8.5	None	None	None	> 20	< 5	8	---	---
F	OT / 8.7–8.9	Ammonia	Oxygen	CPO and DAO	---	70–200	54	< 1, up to 8 at startup	< 1 (HP), 4–45 (LP)
G	OT / 8.7–8.8	Ammonia	Oxygen	CPO and DAO	---	100–150	54	< 1/10	---
H	AVT(R) / 9.0–9.3	Ammonia	Carbo-hydrazide	CPD	10-20	< 5	73	10	---
I	OT / 9.1 (was 8.6)	Ammonia (based on SC)	Oxygen	CPO and DAO	---	75–100	60	< 1	< 5
J	AVT(R) / 9.5–9.7	Ammonia	Carbo-hydrazide	CPD	< 30	< 5	54	---	---
K	AVT(R) / 8.6–8.9	None	Carbo-hydrazide	GSC	7.5	---	33	---	---
L	AVT(R) / 9.2	Ammonia	Carbo-hydrazide	CPD	---	< 1–2 000	19	---/ < 2	---/ < 5
M	AVT(R) / 8.8–9.2	Ammonia	Hydrazine	CPD/ After HCs	> 25	5–10	80	---	---
	OT / 8.0–8.5		Oxygen		< 10–> 20	45	100	0.25–3	0.3–8.5

Table 2:

Cycle chemistry characteristics relevant to FAC.

OT: Oxygenated treatment
SC: Specific conductivity
BFPS: Boiler feed pump suction
HC: Hydrogen coolers
LP: Low pressure
AVT(R): Reducing all-volatile treatment
CPD: Condensate pump discharge
LPFWHI: Low pressure feedwater heater inlet
EI: Economizer inlet
CPI: Condensate polisher inlet
AVT(O): Oxidizing all-volatile treatment
DAO: Deaerator outlet
GSC: Gland steam condensers
HP: High pressure
CPO: Condensate polisher outlet
--- Not known (or not measured in over 5 years)

steel surfaces – whether damaged or undamaged by FAC – with service temperatures within the range of susceptibility, about 50–300 °C (122–572 °F). Areas most likely to be accessible for visual inspection of surface color include deaerators (and storage tanks), boiler feed pump internals, and most importantly LP and HP feedwater heater tube sheets. Reducing conditions, as can be established when reducing agents are used and dissolved oxygen control is satisfactory, will produce a black oxide and surface coloration. Oxidizing conditions exist when no reducing agent is added to the feedwater or when operating with OT. An oxidizing condition will also exist when the dissolved oxygen content of the water is higher than can be controlled by the addition of a reducing agent. Many examples illustrating the color of internal surfaces associated with reducing and oxidizing treatments were presented in the earlier technical review article [1].

Among the plants evaluated, there were some instances where the color of the deaerator, boiler feed pumps, and high pressure feedwater heater tube sheets was not consistent with the feedwater treatment program and associated chemistry data. This is most typically the case where a reducing agent is added but the air in-leakage (AIL) program is not adequate to maintain a condensate dissolved oxygen level less than 10 $\mu g \cdot kg^{-1}$. In many of the drum units where a reducing agent was utilized and the color of the feedwater components should have been black (indicating magnetite), these surfaces were often red (indicative of ferric oxide hydrate, which forms under oxidizing conditions). Though this apparent oxidizing environment may reduce the susceptibility to single-phase FAC, it is not optimized to control copper corrosion in mixed-metallurgy systems.

Oxidizing-reducing potential (ORP) analyzers now are used at many fossil plants with mixed-metallurgy feedwater systems to verify a feedwater reducing environment has been established and is being maintained. (They are not needed in all-ferrous systems.) However, the plant surveys revealed cases where the ORP indications were not confirmed by the color of internal surface oxides or the analyzer was not installed at the proper location (deaerator inlet for units with a deaerator). Plant operators are advised to take advantage of color as an important means of verifying treatment effectiveness and FAC control.

Plant	Locations / types of damage								
	Feedwater piping and carbon steel heater tubes					Drain piping		Feedwater heater shells	
	Low pressure	Deaerator and boiler feed pump	Attemperation		High pressure / EI	Low pressure	High pressure	Low pressure	Deaerator
			Superheat	Reheat					
A					D (type was to be confirmed)	D	T, D		T; extensive
B		D							
C		D	D				D		
D		D					D		No DAs
E		T	T	T		T	T		T
F						D	D		D
G						D	T, D		D
H							D		
I	D	D			D	D	D		D
J		D							
K						D			
L									
M *	P	P		P	D	P	D	P	P

Table 3:

FAC experience profiles: Locations and types of damage.

D: Damage-type of FAC unconfirmed (includes prior inspection results, many 10+ years before)
S: Single-phase FAC damage T: Two-phase FAC damage
P: Predicted damage areas / inspections planned. Blank spaces indicate no confirmed (by damage or inspection) or predicted (by code) areas with FAC.
DA: Deaerator
* 630 MW unit

In addition to proper selection of the treatment, additional action is needed to ensure that application of the treatment is verified as optimal, meaning that the unit is operated under conditions under which concentrations of total iron and copper in the feedwater are minimized to $< 2\ \mu g \cdot kg^{-1}$. (Reduction of condensate total iron to $< 10\ \mu g \cdot kg^{-1}$ is optimal in cases where the unit includes an air-cooled condenser (ACC) [3].) Achievement of this level of total iron indicates that both singe-phase and two-phase FAC are nominally under control. This should be accomplished by means of a survey of corrosion product transport, periodically repeated as needed to ensure continued satisfactory performance. When total iron levels in the feedwater are $> 2\ \mu g \cdot kg^{-1}$, the possibility of two-phase FAC, which is not controlled by the chemistry, still must be considered. Testing for total iron in drains and other points within the cycle is generally helpful in identifying areas of concern in the drain piping though many units are not equipped with sample lines from the HP and LP heater drains. Copper values above $2\ \mu g \cdot kg^{-1}$ indicate the reducing environment is not being properly maintained while the pH is likely less than the optimum range of 9.1 to 9.3 for mixed-metallurgy systems.

At many of the surveyed plants it was determined that very little recent effort had been given to testing of total iron in the feedwater. Even less common was application of valid sampling and analysis of drains samples for total iron with the purpose of identifying sources of active two-phase FAC to optimize control in the drain lines and the alternate drain lines. (As noted earlier, sample lines for the drains are often unavailable.)

Though some of the plants surveyed conducted iron testing using integrated corrosion product monitors or utilized quarterly grab samples analyzed for total iron by outside labs, many of the plants monitoring iron utilized a spectrophotometric test method to measure iron on site. The spectrophotometric tests have two major limitations for determining the iron concentration in the feedwater. The first is that they typically only measure dissolved iron unless proper preconditioning (digestion) of the sample is performed. This is not done in all cases. Secondly, the detection limit of these methods is $> 2\ \mu g \cdot kg^{-1}$ and thus inadequate for optimizing the feedwater treatment.

Plant	Corporate directive for FAC program?	Program approach	Primary inspection basis / prior predictive code analysis?	Chemistry optimized to minimize FAC*	Inspection techniques used	Repair approach		
						Geometry	Materials	Weld overlays
A	No	Reactive	Yes	No	UT, V	RIK	CS	---
B	No	Inspection only	Inspection company / No	No	UT, V	RIK	CS	NR
C	No	None	Damage / No	No	UT	RIK	CS	---
D	No	Reactive	Leaks / No	No	RT	RIK	CS	---
E	No	Reactive	Internal experience / Yes	No	UT, V	RIK	CS, Cr	CS
F	No	Reactive	Yes	No	UT, V	RIK	CS	---
G	No	Reactive	Yes	No	UT, V	RIK	CS, Cr	
H	No	Reactive	Inspection company / Yes	No	UT, V	RIK	CS	---
I	No	Reactive	Inspection company / Yes	No	UT, V	RIK	CS	---
J	No	Reactive	Yes	No	UT, V	RIK	CS	---
K	No	Inspection only	Inspection company / No	No	---	RIK	CS	---
L	No	Reactive	Inspection company / No	No	---	---	---	---
M	No	Reactive	Damage / Yes (recent, for one unit)	No	UT, V	RIK	CS	---

Table 4:
Historical FAC management approach.

* In many instances the plant selected the right chemistry but neglected to take all needed steps to optimize it for minimized FAC.

Inspection techniques: UT: Ultrasonic testing; V: Visual (often following damage); RT: Radiographic testing

Repair approach: RIK: Replace in kind; CS: Carbon steel; Cr: Chromium (≥ 1.25 % Cr) alloy; NR: No repairs

Each of the once-through units assessed was operated with OT chemistry, at reduced pH (controlled by ammonia), though all had previously been operated on AVT(R) at higher pH until OT was introduced. This factor is critical when evaluating points to inspect for FAC as significant damage could have occurred while operating under reducing conditions. However, the FAC program assessment process indicated that none of the programs was optimized at the surveyed plants from either an FAC or unit chemistry point of view, and that some steps needed to optimize the chemistry had not been taken.

- In many cases, oxygen was being fed to two locations while deaerator and heater vents remained open, thereby not allowing full passivation of the deaerator and the storage tank and also minimizing entry of oxygen and ammonia into the drain lines.
- The operating pH range followed was sometimes not optimal to ensure minimum corrosion in the two-phase locations when operating with the vents open. There was, in many cases, little or no attention given to total iron monitoring; thus the effects on corrosion and iron transport went unrecognized.
- As noted earlier, little if any emphasis was given to steam turbine and condenser air in-leakage control in many instances, resulting in condensate pump discharge (CPD) dissolved oxygen readings well in excess of 10 $\mu g \cdot kg^{-1}$.
- On-line water chemistry analysis capabilities were commonly below the Fundamental Levels suggested by the authors. Compliant instruments, in addition to being installed and operational, must have the signal directed to the control room with alarms to alert the operators to chemistry excursions.
- Many of the once-through units on OT are not monitoring dissolved oxygen at the CPD as the original analyzer point was shifted to downstream of the condensate oxygen injection point to provide feedback control.

With one exception, the surveyed units with drum-type boilers were operated on AVT(R). Ammonia and carbohydrazide were typically employed as the pH control and reducing agents, respectively. Some of the units assessed were using hydroquinone as the reducing agent and cyclohexylamine as the neutralizing amine to control pH. One plant fed an excess of reducing agent and relied on the ammonia produced to set the pH; this practice should be discouraged as it can result in an excessively strong reducing environment and lower than optimal pH. Dissolved oxygen in condensate and feedwater were often at concentrations which would interfere with establishment of reducing conditions as desired with AVT(R) for mixed-metallurgy systems. However, in many instances, this could only be considered by inference based on the observed surface color as mentioned previously.

Included in the drum boiler plants is one unit at Plant B where use of AVT(R) continued following replacement of all copper-based feedwater tubing with stainless steel. This change in materials in combination with reducing feedwater treatment, reported excellent control of dissolved oxygen, reducing ORP and a low operating pH range had served to increase the susceptibility to single-phase FAC damage. This plant was advised to initiate efforts to convert to AVT(O) and optimize the pH consistent with results of iron testing.

Only one plant (Plant E) operated its drum boiler units with AVT(O) chemistry. It is an unusual but informative case, where no feedwater treatment chemicals have been used for essentially the entire 50+ years of service operation. Minimal on-line chemistry instrumentation was provided and no significant testing of iron and copper had been performed. The feedwater pH was typically less than 8.5 and often less than 8.0, however, dissolved oxygen control, while not optimal, was better than in many of the fossil plants surveyed for FAC (Table 2). Discussion of known FAC damage in the units at this plant including review of several laboratory assessments ultimately confirmed that there was widespread two-phase FAC with no apparent single-phase FAC. The low pH feedwater condition in these units results in much lower pH of the liquid phase in the two-phase flow locations. This is conducive to dissolution of magnetite and two-phase FAC. The oxidizing conditions (no reducing agent) have resulted in predominantly red surfaces in the single-phase flow areas providing a sharp contrast with the black shiny areas where the two-phase flow and FAC occur. Consistent with most of the other plants surveyed where two-phase FAC damage had developed, it tends to remain active until the pH is elevated considerably (9.6 or greater). Two-phase damage in the units at this plant resulted in leaks developing in a number of locations, including several in the high pressure feedwater areas as indicated in Table 3.

FAC DAMAGE EXPERIENCE AT PLANTS ASSESSED

Generally, the plants had experienced damage and in many cases minor leaks determined to be the result of active FAC damage. One of the plants had not determined any apparent FAC damage in its units; however, this result was based on minimal inspection activity. See Table 3 for a summary of experience.

Single-phase FAC damage was generally clustered around the boiler feed pumps and nearby components including the deaerator piping, feedwater regulating stations (where part of the cycle design) and spray attemperation piping. Concentration of single-phase damage at these locations directly relates to the governing science and is consistent with worldwide experience, which also includes several cases of single-phase damage in the economizer inlet area [1]. Any failure downstream of the discharge of the boiler feed pumps will be much more severe than the condensate system due to significantly higher pressure.

Two-phase FAC damage was predominant in drains, concentrated in two areas. The first was the high pressure cascading drains piping. Alternate drains, used generally at startup and for heater level control, were also subject to FAC damage in many instances. Areas of damage consistently related to pressure differentials between the source and recipient components and the associated flashing potential, in combination with drain usage practices. Similarly, two-phase damage had developed in the shells of the deaerators at several of the surveyed plants, at locations where drains returns were subject to flashing. Again, this distribution reflects the science as well as industry experience. Determination of the extent to which various heater drains and bypass lines were used and thus subject to flow was only possible through discussion with plant operations personnel.

The influence of pH on single-phase FAC damage with reducing chemistry treatment has been investigated extensively and is now well recognized. However, many of the surveyed units, particularly those with AVT(R) feedwater chemistry, were not operating at pH levels normally needed to minimize dissolution of magnetite. Organizations still continue to operate with feedwater in relatively low pH ranges (approaching 9 or even lower); this is not optimal and has proven dangerous in other plants. This was highlighted in the recent review as being one of the most serious situations leading to FAC damage/failure [1]. In some of the case studies the pH was kept low because of copper alloys in the feedwater system but in a number of instances the organizations continued to operate in the low pH ranges even after the copper heaters had been replaced with stainless or carbon steel. In addition, the confirmatory total iron analyses were not performed in many instances.

Seemingly less well recognized is the effect of low feedwater pH on two-phase FAC damage rates. Operation with low pH in the feedwater (at single-phase flow areas) will result in the liquid in the two-phase flow areas (produced by flashing) being at an even lower pH. As a consequence of this the solubility of magnetite at this lower pH increases and gives rise to a higher FAC rate at these locations. Inadequate effort to optimize oxidizing feedwater treatments (particularly OT at lower pH of 8–9) allows FAC damage (both single-phase and two-phase) in the drains piping to continue and, quite possibly, to become worse.

FAC MANAGEMENT APPROACH

A properly implemented and comprehensive, company-wide, multidisciplinary approach to FAC management as suggested by EPRI is both efficient and effective. Based on worldwide experience it is clear that world class FAC programs must include the following features to be both proactive and effective:

1. A corporate mandate which clearly delineates required actions and responsibilities:
   - Applied across the organization and coordinated by a responsible team;
   - Staff driven with multidisciplinary involvement;
   - Continuous activity to ensure that the latest technical information and field experience is considered.
2. Use of a predictive process (either engineering experience as used in the current studies or a predictive code) to identify locations subject to a high vulnerability to FAC damage with results used to target follow-up inspection activities.
3. Selection of feedwater treatment consistent with the unit characteristics, particularly the feedwater heater tube materials. Systems with all-ferrous feedwater heaters should be operated on oxidizing treatments. Optimal treatment for OT with pH levels below 9 requires effective air in-leakage control to allow operation with heater and deaerator vents closed. Drum units on AVT(O) should operate at higher feedwater pH (9.2 to 9.6).
4. Units with copper materials in the heaters require reducing treatments. Again, air in-leakage minimization is important in this instance to ensure that reducing conditions are maintained throughout the entire feedwater system. Operate at pH that also reduces iron transport (9.1 to 9.3).
5. Units with both all-ferrous and mixed-metallurgy feedwater systems must know the levels of total iron and copper so as to have cycle chemistry optimized to reach the established minimums ($< 2\ \mu g \cdot kg^{-1}$). Scope of testing should include the boiler feedwater and the low and high pressure cascading drain lines. It should include the CPD if the unit includes an ACC, with iron levels $< 10\ \mu g \cdot kg^{-1}$ possible when the treatment is optimized by operating with a condensate pH of 9.8 or higher [3]. Iron analysis is only needed at approximate six month intervals once cycle feedwater treatment and FAC are optimized.
6. The shell side of LP heaters and deaerators must be inspected for two-phase FAC damage.
7. Drain lines and alternate drain lines are considered primary locations for inspection, particularly for two-phase FAC. Emphasis should be given to locations of likely flashing to produce two-phase conditions and significant local turbulence.
8. Requirements that action plans be developed and implemented to deal with repair or replacement of components damaged by FAC.
9. The corporate mandate should be refreshed at least once per year to ensure the corporate FAC program is an on-going process, with action initiated when needed to consider changes in unit materials, cycle chemistry, and operation. For example, it is important to consider feedwater chemistry and FAC susceptibility when feedwater heater tubing is changed from copper alloys to stainless steel.

These features are not randomly disconnected; they are the essential integrated attributes of highly effective programs. Failure to include each of these features is an indication that FAC is likely to be active somewhere in the cycle.

In contrast, none of the FAC programs assessed was completely comprehensive (Table 4). Most plants have periodically adopted partial programs. The word best describing these programs is reactive, whether to previous leak incidents on the unit or elsewhere in the industry. This is consistent with the broader fossil industry, where periods of high interest in FAC have followed the incidence of FAC events resulting in personnel injuries/fatalities or serious damage to plant equipment. After some period of providing attention to FAC (typically a year or two), organizations transfer their interest to something more (or less) important!

Efforts during these high interest periods have usually focused on either the cycle chemistry side or, more frequently, the inspection and nondestructive evaluation (NDE) side. Usually they have not effectively combined the two. To be optimally effective a comprehensive program should provide expertise to proactively deal with the complete cycle chemistry, prediction, inspection, NDE, repair and management aspects.

Use of computer programs intended to evaluate FAC susceptibility varied. Only one plant (plant M) had made a recent predictive assessment for FAC in a unit, the results of which were to be used for planning of future inspection activities. In some cases an internal computer assessment had been made, often over 10 years ago. In others an outside party had made a computer assessment. Others had performed no computer assessment. The low level use of FAC predictive codes in fossil plants as compared to nuclear plants relates directly to the fact that there aren't any comprehensive fossil-specific codes available which adequately deal with the full range of feedwater chemistries used in fossil plants. It is also important to determine if the use of a predictive code will cover the two-phase situations which have been identified during the plant investigations summarized in this paper. It should also be noted that the earlier predictive efforts did not fully reflect the latest understanding of FAC and/or did not account for changes in unit characteristics since the work was conducted. In cases where the program was used internally, the original user had sometimes left the organization without any arrangement made to transfer responsibility for use of the program.

Plants assessed generally recognized the potential danger associated with making repairs which included changes in geometric conditions; the feedback across the board was that "in kind" replacements were typically made. Here it should be understood that changes in local turbulence resulting from geometric changes intended to prevent further damage most often result in shifting the damage pattern without eliminating damage susceptibility. Most of the organizations understood that use of steels with increased chromium content (1.25 % Cr or greater) to replace components damaged by FAC is needed to mitigate further damage. Some plants previously replacing with carbon steel had switched to low alloy material for their latest two-phase FAC situations. Similarly, should weld overlay be considered (for locations such as inside deaerators and heater shells), a suitable chromium alloy weldment should be used.

CONCLUDING REMARKS

Important conclusions from the recent work are as follows:

1. Two-phase areas of the cycle are very susceptible to FAC, especially where the temperature and pressure changes across control valves and expanders are greatest. Effects are now being more frequently observed in intermittently operated piping such as auxiliary (high level or emergency) drains.
2. Conflicts sometimes exist in results for oxidizing and reducing potentials and dissolved oxygen versus the color of the equipment. This means single-phase FAC susceptibility cannot be determined based purely on the reported chemistry results. Color of surfaces is always the true and better indicator of local chemistry environment during service and thus confirms whether FAC can occur. Action is needed but not always taken to investigate and improve chemistry surveillance capabilities when observed color is different than suggested by the feedwater chemistry results.
3. Low pH conditions continue to be dangerous with respect to single and two-phase FAC damage potential. This is always a concern in drains piping, and is especially important on units operating on OT when the heater vents are open.
4. The cycle chemistry needs to be fully integrated into an FAC program and the cycle chemistry optimization process needs to consider FAC susceptibility throughout the cycle. Many of the plants surveyed have selected the chemistry correctly but not taken all of the actions needed to optimize its application so as to minimize FAC. Others have not acted to properly reassess the chemistry needs of the unit following a change in cycle materials.
5. Effective use of inspection and NDE as a tool is not applied throughout the industry. At some of the units surveyed (all in service for > 35 years) there was minimal or no inspection history.

Given the accrued service hours of the many fossil units, it seems likely that improvement in FAC management is needed as none of the organizations surveyed had comprehensive programs.

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