Presented at the EPRI 9th Ninth International Conference on Cycle Chemistry in Fossil and Combined Cycle Plants with Heat Recovery Steam Generators, Westin Copley Place Hotel, Boston, Massachusetts, June 29-July 1, 2009.

EPRI's Guideline on Chemistry for Fossil Units with Air-cooled Condensers (ACCs)

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Abstract

This presentation provides the results of the first worldwide survey of a number of fossil and combined cycle/HRSG plants with air-cooled condensers (ACCs). It includes: a) the development of moisture nucleation throughout the ducting system from the steam turbine to the ACC tube entries, b) documentation of the surface condition of the duct surfaces

annotating the specific corrosion events, c) defining the serious corrosion/FAC regions, d) the interim guidelines for operation of plant with ACCs [1].

Introduction

In any steam-water power cycle design, provision must be made to condense the turbine exhaust so that it may be returned to the steam generator as feedwater. The coolant traditionally employed for this purpose has been water since it was normally inexpensive, efficient and abundantly available. However, this is not always the case; the first known application of dry cooling to a power generation cycle dates to 1939. Over the next 70 years interest in dry cooling methods, including introduction of direct cooled air-cooled condenser (ACC) designs continued and slowly grew, with installations in industrial steam/power and other applications, including fossil power stations.

Selection of cooling technology for use in power plants is an economic decision which is frequently influenced by local environmental and political factors. In the early days, use of dry cooling methods was sometimes the only feasible option due to scarcity of water at otherwise attractive plant sites in arid and semi-arid regions of the world. However, the combined trends of increasing demands for power, more widespread scarcity of available water for cooling and increasing costs of water and tighter environmental restraints related to use of wet cooling systems served to broaden selection of the ACC option, in term of both number and size of units.

Figure 1 depicts the trends in installation of ACCs and indirect dry cooling systems on units >100MW since 1960. (Indirect designs employ water cooling of turbine condensate in a closed system arrangement with air-cooled exchangers used to reject the heat transferred to the cooling water during condensation.) From this figure it quickly becomes apparent that increased interest started around the mid 1980s and has generally continued to grow, particularly over the last 10 years. Figure 2 notes construction of dry cooling systems (largely ACCs) around the word. It indicates that interest in ACCs is indeed global. Not surprisingly, China dominates the scene consistent with efforts to expand fossil generating capacity. ACCs are now in use at or planned for an ever-growing number of conventional and combined cycle plants. This dramatic increase in the application of dry cooling confirms that this technology is now well established in the power industry. As dry cooling provides an advantage of dramatically reducing water consumption it provides more flexibility in power plant site selection. In many cases, selection of dry cooling expedites the permitting process as well.

Mechanical draft ACC systems account for all direct dry cooling used in power plant applications. Latent heat contained in the turbine exhaust steam is directly transferred to the ambient air stream without an intermediate cooling water circuit. Heat transfer is achieved without any evaporation or loss of water from the circuit. The main components of a typical air-cooled condenser are shown schematically in Figure 3.

In cycles with ACCs, turbine exhaust steam is conveyed as a two-phase fluid from the turbine exhaust hood via large diameter duct(s) to one or more steam distribution headers from where the steam is distributed into finned tubes where most of the heat transfer from steam to air takes place. The finned tubes are arranged in the form of an A-frame. Steam enters the finned condensing tubes and flows downwards. Both condensate and excess steam are collected in a bottom header. The excess steam in the condensate header is drawn into and condensed in a second stage of the ACC called the dephlegmator. Non-condensable gases are collected in the top part of the dephlegmator tubes from where they are passed to the air removal system. Cooling air is forced across the finned tubes by means of axial flow fans. A typical ACC of direct cooled design in use at a large combined cycle power station is shown in Figure 4. Some of the risers and steam distribution headers are shown. The condensing and dephlegmator tubes of the A-frame are above the fans and behind the wind screen structure.

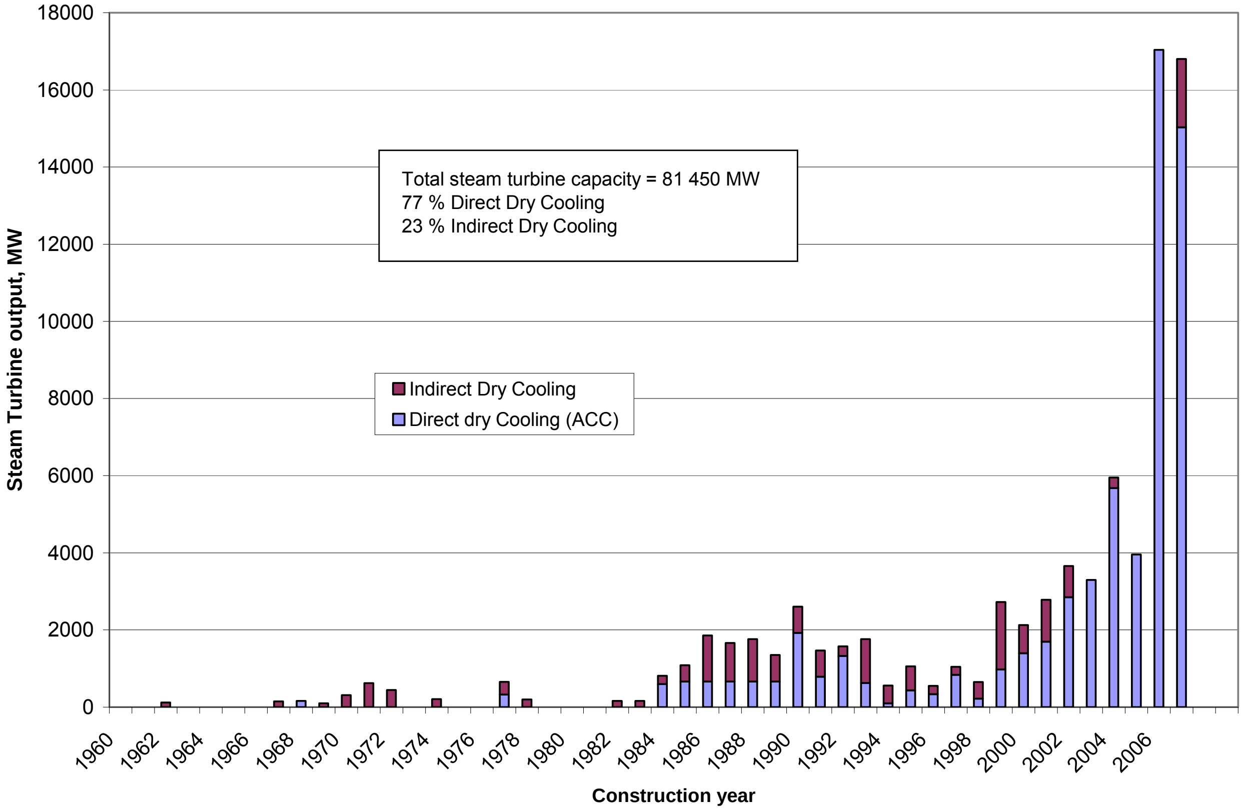

Figure 1
Worldwide installation of dry cooled power plant shown as the output of the steam turbine as a function of the year the plant was constructed [2-6].

Guidelines Project Objective and Activities

As ACCs were introduced across the fossil industry, experiences and observations pertaining to the cycle chemistry came to the attention of EPRI. Chief among these was iron transport. Levels of iron in the boiler or HRSG feedwater were noted to be higher and in many cases substantially higher than desired or expected when following the applicable EPRI Chemistry

Guidelines. Increases in iron transport were associated only with ACCs; indirect dry cooling designs were not substantially different from water-cooled condensers (WCCs) with respect to iron release. Internal inspections of ACCs confirmed the presence of damage, which appeared to account for the high iron concentrations. In addition, the need for condensate polishing and filtration systems, as well as the basis for selection and operation of such systems was called into question. Finally, it was known that a number of end users treated their combined cycle units with chemicals other than those suggested in the guidelines. Of specific interest here was the use of neutralizing amines, including proprietary amine blends, instead of ammonia for feedwater pH control. In response to member interest and support, EPRI initiated activity to investigate the situation and provide guidance specific to units with ACCs.

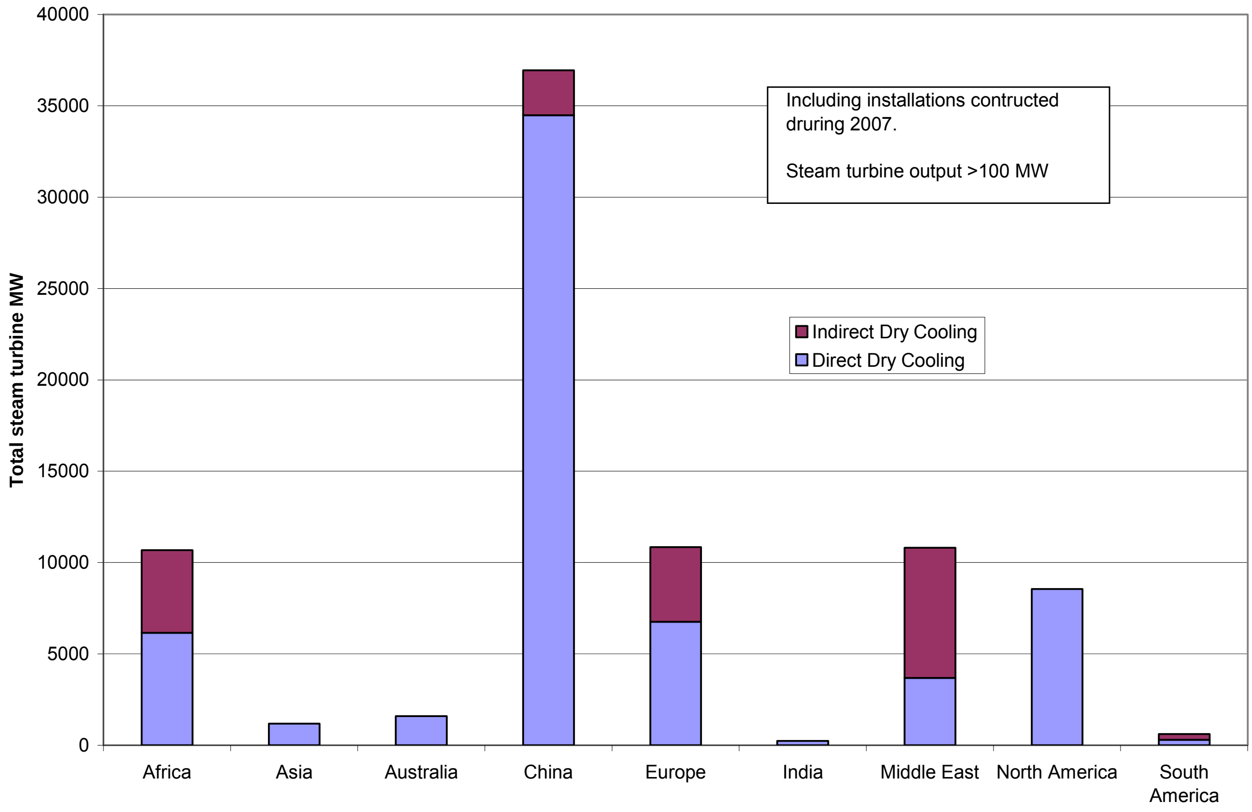

Figure 2
Total dry cooled installed capacity in 2007 by geographic region [2-6].

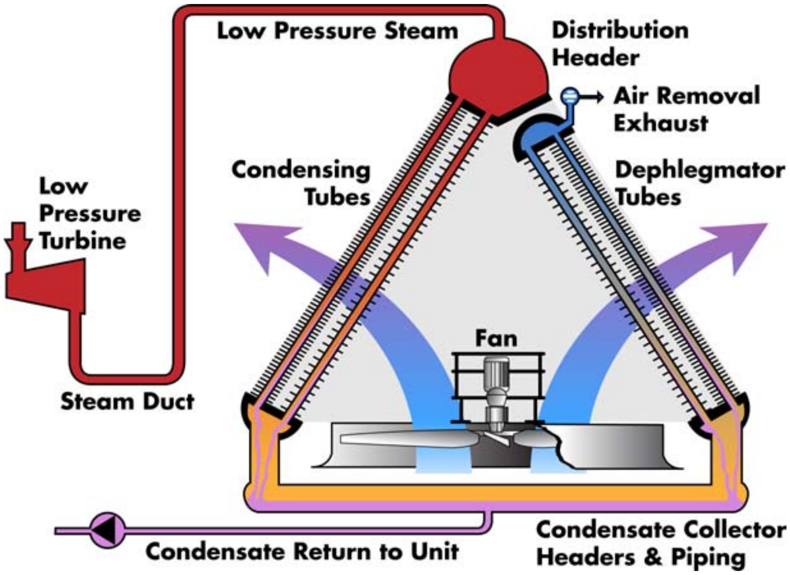

Figure 3
Air-cooled condenser schematic.

Source: Adapted from Reference 7 [7].

Figure 4
Air-cooled condenser showing three (of five) steam distribution ducts.

Source: John Maulbetsch

The overall objective of the project was to consider the cycle chemistry requirements of fossil units with ACCs of direct cooling design and establish interim guidelines for units subject to high levels of iron transport when following the EPRI guidelines for units with water-cooled condensers. To satisfy this objective it was necessary to:

- Appraise end user awareness and experience.

- Become familiar with the responsible mode of damage, leading to iron entering the condensate.
- Consider the role of the chemistry, if any, in producing the damage.
- Identify possible changes in chemistry which could be implemented to ameliorate damage.
- Consider any consequences of any proposed changes in chemistry on other areas of the steam-water cycle.

Data collection involved a combination of literature search efforts and communications with various stakeholders including ACC end users and manufacturers. A series of field visits was made to exchange information. However, by review of the published literature and communications with end users, it could not be verified that sufficient definitive and technically valid failure analysis examinations had been conducted and published. It is now apparent that not all of the organizations which operate units with ACCs had made internal in inspections of them. Thus it is not entirely surprising that so little work has been done to evaluate damaged tubing metallographically. Some of the organizations visited during the project arranged to make internal inspections of the ACC during the visit while others indicated they would seek to include an ACC inspection in the schedule of the next extended outage.

Assessments of Damaged Tubing

Findings of a singular ACC tube examination by Dooley provided some insight but additional corroborative exams were felt to be needed [8]. Since the project was completed another tube assessment has been performed [9]. Findings of this most recent exam are largely consistent with those of the prior evaluation. In summary, the investigations point to a corrosion mechanism generally consistent with two-phase flow-accelerated corrosion (FAC) at low temperature in other areas of fossil cycles [8-10]. Deposition of magnetite released by this corrosion on nearby surfaces was also confirmed. Further, there is no evidence of erosion or impingement damage.

Characteristics of the Two-phase Fluid in the ACC System

Extensive investigations have been conducted to understand the moisture nucleation process in the phase transition zone (PTZ) in the low pressure (LP) section steam turbines including effects of electrostatic charge of moisture droplets [11]. Far less is known about conditions within and beyond the LP turbine exhaust. A two-phase mixture of water and steam exits the low pressure turbine, and is directed to the top distribution ducts of individual ACC modules via a network of transfer ducts. This arrangement results in contact with a far greater area of carbon steel surface than occurs in units with a water-cooled condenser (WCC).

In general, nucleation of moisture droplets can occur either heterogeneously or homogeneously. The latter commences at lower degrees of supercooling, while the former requires condensation nuclei to start the process, and a continuing supply of such nuclei for nucleation to continue. Homogeneous nucleation involves random collisions between molecules and molecular clusters. Superheated steam approaching the PTZ or saturation line typically contains an adequate supply of ions and charged particles to act as nucleation centers, and initial water droplets begin to form at around 3-4% supercooling in the steam turbine and continues until there is between 7 and 15% moisture (depending on the turbine and the plant) exiting the last stage blades and entering the exhaust hood. These initial or first condensate liquids (droplets) have decreased pH by up to one unit and elevated levels of anions. Without any further extraction of heat and a fresh supply of nucleation centers, further condensation cannot occur until, in a water-cooled condenser (WCC), the two-phase mixture enters the condenser and supercools. Homogeneous nucleation and condensation of the remaining steam then takes place. In summary, the condensation mechanism is a two step process with initial condensation occurring heterogeneously on ions and foreign species. The bulk condensation occurs homogenously within the condenser following supercooling.

In units with an ACC the initial heterogeneous nucleation occurs similarly within the PTZ of the steam turbine, and a two-phase mixture leaves the last stage blades. The moisture content here is both plant and turbine specific. Moisture droplets will have a lower pH and increased levels of anions compared to the bulk fluid. This mixture flows through the transfer ducts to the ACC and enters the condensing tubes with generally minimal heat transfer and condensation (though the condensation which does occur is sufficient to produce a liquid film on some surfaces contacted by the fine moisture droplets). Most heat transfer and condensation takes place in the ACC tubes, which allows most of the remaining moisture to nucleate. The final part of the condensation then takes place in the dephlegmator tubes.

Characteristics of Plant Sites Visited

In all, 11 fossil plants with ACCs were visited during the project. Ten of the plants operated mechanical draft direct cooled ACCs. The remaining plant had ACCs of indirect design; it was included to illustrate the difference in iron transport when operated within EPRI Cycle Chemistry Guidelines.

Some general demographics for the ten plants with direct cooled ACCs are as follows [1].

- Five plants with conventional boilers included 17 units with ACCs with installed between 1978 and 2006.
- Five plants with heat recovery steam generators (HRSGs) included five combined cycle units with ACCs installed between 1996 and 2004.
- Most of the plants included ACCs of multiple row bundle designs but one was of single row design. This plant also featured a sloped main duct whereas horizontal ducts were provided in the units of the other plants.

This plant population includes both conventional and combined cycle units. It also reflects the latest generation of ACC design as well as some older designs with considerable time in service.

The population of visited plants with direct cooled ACC designs utilized various feedwater treatment approaches. The following statistics summarize this and reflect varying levels of end user awareness with respect to iron release from ACCs [1].

- 80% of the plants practiced ammonia dosing to control pH while 20% utilized neutralizing amine products.

- 20% of the conventional plants fed a reducing agent (AVT(R) feedwater) while the remaining 80% dosed the feedwater with oxygen (OT feedwater).
- 60% of the combined cycle plants fed a reducing agent (AVT(R) feedwater) while 40% did not (AVT(O) feedwater).
- Iron testing had been performed by each organization; however. In some cases testing was performed infrequently and little data were available. In others, data validity could not be verified.
- Condensate polishers were provided only on the units at the plants operated on OT chemistry; one of these systems also included pre-filters. Two other plants (one a conventional cycle, the other a combined cycle) provided condensate filter systems.

It should be noted that the purpose of periodic iron monitoring is to measure the total iron content of the sample. In power stations, the majority of the iron is normally present in suspended form. Spectrophotometric methods now in use at many plants are developed to measure dissolved iron; digestion of the sample is required prior to analysis but this is not always done. Suspended/undigested iron is a source of interference. Further, in water-cooled cycles with optimized chemistry, total iron levels of 2ppb or lower in feedwater are normally achievable. This is below the reliable detection limits of some methods in common use. A practical discussion of total iron monitoring at low levels attainable with optimized chemistry is provided in the literature [12].

Available inspection and repair information for the ten plants with direct cooled ACCs may be summarized as follows [1].

- 80% of the plants had performed at least a partial inspection of their ACCs.
- Duct damage had been observed in all plants where this area of the cycle had been inspected.
- 70% of the plants confirmed damage in the distribution headers and tubes of the ACC.
- 20% of the plants reported development of through-wall tube leaks.
- Corrective actions that had been implemented at this group of plants included seal welding of leaking tubes (10%), application of coatings and sealants (20%), installation of tube inserts (10%) and adjustment of steam pH (20%).

ACCs are not always “inspection friendly”. Access ladders are sometimes offered as an optional feature which is not always accepted as part of the unit design. Safe entry of an ACC duct at one of the plants visited required use of a crane.

Classification of Damage in ACCs

As part of the survey process members of the project team obtained photographs of internal conditions extant in transfer ducts, distribution ducts and inlet condensing tubes of a number of ACCs. These were evaluated in accordance with an assessment methodology developed and proposed by Dooley and Howell, the Dooley Howell ACC Corrosion Index (DHACI) [9, 10]. Its application requires separate evaluation of conditions in the lower and upper sections of the ACC ducts and the top of the condensing tubes.

Within the upper section (header/duct and tube entries), corrosion located at the tube entries is the most important feature of interest. Five factors have been designated to rank the severity of damage from lowest (1; good condition with no apparent damage and minimal oxide deposition) to highest (5; observation of holes in tubing or welds with severe corrosion over a large number of tube entries).

The lower ducting part of the DHACI applies to the ACC sections from the steam turbine exit through the distribution ducting to the louvers entry at the top of the risers. Three factors, designated as A-C, have been developed to rank the severity. The best ranking (A) is given when ducting shows no signs of two-phase damage. The lowest raking (C) applies to cases where there is severe damage, appearing as white (bare metal) surfaces in the hot box and at numerous locations subject to changes of direction (e.g. at intersections of exhaust ducting to vertical riser).

The DHACI assessment methodology assigns a number (from 1 to 5) and a letter (from A to C) to rank internal conditions in the ACC. Use of DHACI as assessment tool by organization operating ACCs is encouraged as a means of objectively assessing their inspection findings. When applied over time to individual ACCs, the index can be used to track effects of changes or improvements introduced to improve corrosion control.

Application of DHACI does not extend to the entire length of the ACC condensing tubes nor to the lower collection headers and dephlegmator tubes. If warranted based on inspection feedback, expansion of DHACI to include surface conditions in these areas will be considered once a larger number of inspections have been conducted to document their condition.

Interim Cycle Chemistry Guidance for Units with ACCs to Reduce Damage and Iron Transport

In cycle designs which include ACCs operating in accordance with EPRI Cycle Chemistry Guidelines, condensate iron levels have often been found to be considerably higher than those achievable in otherwise comparable fossil units with WCCs, both at startup and in extended service operation. In more extreme cases iron levels in the 100-300 ppb range have been observed with concentrations of >10-25ppb more common. The acuity of the problem has gained greater attention as the demand for new generating units with ACCs increased.

In contrast, units with WCCs can typically achieve <2ppb iron as Fe in the feedwater when using reducing all-volatile treatment (AVT(R)), with lower levels possible if the reducing agent is not required and the unit operates with oxidizing all-volatile treatment (AVT(O)). In units on oxygenated treatment (OT), feedwater iron levels of <1ppb are easily achievable. Iron levels will generally be higher at startup and in cycling operation with actual values reflecting the effectiveness of shutdown protection measures taken.

Given that the damage in ACCs is generally consistent with two-phase FAC damage, it stands to reason that the pH in the droplets and liquid on surfaces would be lower than that of the bulk fluid, especially when using ammonia for pH control. This has been considered via calculation [13] and in one instance measured in the field [14].

Plant survey activities confirmed that operation with ammonia at a higher feedwater pH than indicated in the EPRI Cycle Chemistry Guidelines is beneficial for units with ACCs. A graphical depiction of the Dooley-Aspden Fe/pH Relationship correlates measured condensate pH and iron concentration values. It was developed on the basis of collection and plotting of condensate data from a number of operating plants with ACCs around the world using ammonia for pH control [9, 10]. Maintaining the pH between 9.8 and 10 with ammonia typically reduces levels of iron in the condensate to 10ppb or less. Iron at this level is more easily managed by condensate polishers or filters, when provided. Clearly, the higher pH provides some significant reduction in iron transport from the ACC, though levels may be somewhat higher than achievable in well operated units with WCC designs.

EPRI's feedwater treatment optimization process, based on evaluation of total iron (and, where relevant total copper) transport under controlled feedwater treatment regimes, remains applicable to units with ACCs. However, it should now extend into the pH range of 9.8-10 for units with ACCs when the feedwater system is all-ferrous. EPRI's new interim guidelines for the chemistry of water in cycles with ACCs are presented in Table 1 [1]. There is no change in guidance with respect to steam purity, boiler/high pressure evaporator treatments, allowable contaminant levels, etc.

Note that special care in optimization must be taken in treatment optimization for cycle designs with copper in the feedwater system or that are fitted with mixed-bed condensate polishers as high pH operation may result in other problems. In such cases, the objective is to determine the feedwater treatment regime at which total metals transport is minimized and polisher performance is not compromised.

There are now a number of fairly new units with once-through boilers intended to be operated with OT. Early operation of these units was subject to extensive iron transport problems which continued beyond commissioning on AVT into early commercial operation and conversion to OT with lower pH ranges (8.0-8.5). As these units were fitted with condensate polishers of either mixed-bed or precoat (powdered resin) design the high levels of iron release from the ACC caused immediate concerns including bed pressure drops, short runs and the potential for iron fouling of deep bed media as time in service accrued.

Another concern with polisher operation in units with ACCs (as well as certain units with WCCs) not related to corrosion is the high condensate temperatures, which may exceed the standard maximum allowable values stated by ion exchange resin manufacturers in their specifications. However, field experience in plants around the world has demonstrated that high condensate temperatures can be tolerated, in units with both air-cooled and water-cooled condensers [15].

Table 1
Comparison of Important EPRI Feedwater Target Values: Fossil Units with Air-cooled Condensers [1]

Parameter	**Feedwater Treatment**					
	AVT(R)[1]		**AVT(O)**[2]		**OT**[2]	
	Drum	**Once-through**	**Drum**	**Once-through**	**Drum**	**Once-through**
pH (All-ferrous)[3]	9.8-10.0	9.8-10.0	9.8-10.0	9.8-10.0	9.8-10.0	9.8-10.0
pH (Mixed-metallurgy)[4]	9.8-10.0	9.8-10.0	NA	NA	NA	NA
Cation Conductivity, μS/cm	≤0.2	≤0.2	≤0.2	≤0.2	≤0.15	≤0.15
Iron, ppb (All-ferrous)[3]	≤10	≤10	≤10	≤10	≤10	≤10
Iron, ppb (Mixed-metallurgy)[4]	≤30	≤30	NA	NA	NA	NA
Copper, ppb (All-ferrous)[3]	≤2	≤2	≤2	≤2	≤2	≤2
Copper, ppb (Mixed-metallurgy)[4]	≤5	≤5	NA	NA	NA	NA
Dissolved Oxygen, ppb (All-ferrous)	1-10	1-10	1-10	1-10	30-50	30-150
Dissolved Oxygen, ppb (Mixed-metallurgy)	<5	<5	NA	NA	NA	NA
Sodium, ppb	≤3	≤3[5]	≤3	≤3	≤2	≤2[5]

Notes:

1. Reducing agent should be added to establish reducing environment.

2. Reducing agents are not required and should not be used.

3. Metals concentration is measured ahead of condensate polisher or filter (where provided). Optimize pH consistent with monitoring results for iron. In units with condensate polishers, operation at lower pH may be needed to avoid high ionic (mainly sodium) leakage from mixed beds which do not follow a cation bed and from powdered resin polisher systems.

4. Metals concentration is measured ahead of condensate polisher or filter (where provided). Optimize pH consistent with results for monitoring iron and copper. In units with condensate polishers, operation at lower pH may be needed to avoid high ionic (mainly sodium) leakage from mixed beds which do not follow a cation bed and from powdered resin polisher systems.

5. Measured at Condensate Polisher Effluent.

Use of Alternate Feedwater Treatment Chemicals in Units with ACCs

The EPRI Cycle Chemistry Guidelines for feedwater were developed on the basis that ammonia (ammonium hydroxide) would be used as the preferred pH conditioning agent. Further, hydrazine was designated as the preferred reducing agent, where use of such treatment is needed. These designations were made in consideration of widespread experience demonstrating successful use of these treatments, general availability and low cost, and the fact that their breakdown products contained no organic compounds or carbon dioxide, thus having no impact on cation conductivity measurements. Nonetheless there has been some use of alternative treatments in conventional fossil and combined cycle plants for various reasons.

The project identified no connection between ACC damage and use or non-use of reducing agents. Thus the interim guidance does not extend to these treatments. Their use is indicated only in plants where there is copper in the feedwater part of the cycle. Addition of reducing agents in all-ferrous cycles is discouraged as experience has shown a higher incidence of single-phase FAC damage in units using them.

Some further points need to be considered when using alternate amines (including blended amine products). The potential for better protection of the ACC at a given operating pH may exist due to favorable differences in amine volatility and/or basicity properties, as compared to ammonium hydroxide as suggested by Bignold [13]. However, this claim is not fully substantiated in fossil units. Of the organizations known to operate fossil units with ACCs on amines, few if any have been subjected to proper iron transport assessment and internal inspection of surfaces subject to corrosion. Thus the Dooley-Aspden Fe/pH Relationship currently does not consider these alternate amines due to insufficient information on any individual treatment.

As mentioned earlier, neutralizing amines (and reducing agents used as alternative treatments to hydrazine) are subject to thermal breakdown at elevated temperatures and pressures; it is uncertain how much of the amine fed to feedwater remains following passage through a boiler or HRSG. Use of neutralizing amines is more common in nuclear plants and industrial facilities where thermal breakdown is of lesser concern because these systems operate at lower temperatures than are present in high pressure fossil boilers and HRSGs. Polyamines are another group of treatment chemicals which could be added to cycles with ACC, but no field information on their application was available during the project.

Neutralizing amines should only be used for feedwater pH control with great caution if the unit design features a condensate polishing system, especially if it is of mixed-bed design, since the available information on ionic leakage at high pH indicates that leakage will be even higher than when operating with cation resin in the ammonium form. Further, amines may influence resin fouling tendencies and the filterability and deposition characteristics of particulate oxides. Additional research leading to positive results would be needed to determine if amines can effectively be used under such circumstances.

When alternate feedwater treatment chemicals are used, the operator is strongly cautioned to be aware of the many uncertainties surrounding their application during efforts to optimize the chemistry including pH optimization and assessment of condensate polisher performance. Experience of the authors suggests that this is frequently not done properly.

Actions for End Users and Some Possible Future Research

Based on the work conducted during the project, end users operating plants with ACCs are well advised to initiate any of the following actions that are not already a part of their program:

- Conduct ACC duct and tubing inspections during all major/scheduled outages.
- Document inspection findings with photographs.
- Use the DHACI tool to evaluate and rank conditions and general appearance of the ACC interior ducts and condensing tube inlets. Results provide an objective assessment of corrosion, extent of damage over time.
- Monitor total iron concentrations at the CPD during routine unit operation and at startups with enough frequency to be comfortable that iron levels are both stable and optimized. (Validate applicability of iron test method in use.)
- Perform follow-up total iron monitoring after any chemistry or operational changes are made to evaluate impacts on system corrosion/FAC and/or iron transport. Note that importance of internal inspection is high following such events when they lead to increased iron transport.
- To provide some protection to the ACC when the unit is out of service (longer outages) drain any areas with standing water as soon as possible after unit shutdown.
- Inclusion of a condensate polisher is mandatory when the cycle includes a once-through supercritical boiler. The most common polisher design, employing mixed beds of bead resins, will have very short run lengths unless operated in the ammonium form. Attainment of the optimal pH to reduce corrosion/FAC in the ACC is not likely to be attained when using mixed-beds. Alternate polisher designs exist that are better suited to high pH operation.
- Operator action to monitor and tightly control air in-leakage should be strongly encouraged to simplify feedwater treatment control, facilitate attainment of feedwater chemistry targets, and maximize run times of condensate polishers.
- Condensate filters can be considered as a means of removing some of the iron released to the condensate from the ACC. Optimization of the chemistry offers an opportunity to reduce the need for filters as part of the design as well as the need to consider their retrofit and to extend media life when they are provided.

Many questions have surrounded corrosion in ACCs. Investigations performed during the project provided many useful insights, leading to or supporting many of the suggested actions but also raised new questions to which answers remain unclear. There is still an incomplete comprehensive scientific understanding of the corrosion/FAC processes which emanates from an equal understanding about the environment which exists within an ACC. Clearly a better derivation of cycle chemistry target values and corrosion prevention methodologies will only be developed by first understanding in detail the local environments at surfaces experiencing damage. This could then be accurately simulated in a laboratory corrosion facility. Once the corrosion/FAC processes are accurately simulated then the same equipment can be used to address possible solutions which in parallel can be tested in the field. Thus the following multi-part program could form the skeleton of a comprehensive research effort to address and understand corrosion/FAC in ACC.

1. Metallurgical examination of as many ACC tubes as possible. This is very clearly the most immediate need.
2. Detailed monitoring campaign at plants with ACCs to improve understanding of the local environment. This should include:
    - Temperature monitoring of the ducts and fluid from the steam turbine to the tube entries. Thermal imaging could be used as well to derive approximate temperatures and leakage paths. This will be a difficult task due to the small drop in temperature along the ducts.
    - Two-phase computational fluid dynamics (CFD) modeling of the various known areas of corrosion with particular emphasis on the A-frame tube entries.
    - Cycle chemistry monitoring to more accurately determine the relationship between pH and iron levels at the condensate pump discharge (CPD). Monitoring scope should include units operating on AVT(O), AVT(R), OT and on an amine treatment program.
    - Special chemistry monitoring to determine the environment within the ACC ducting. This would involve extracting condensed fluid at the duct walls during operation and shutdown. There are advantages to collecting this condensed phase as near to the tube entries as possible. Again this should be conducted on units operating on AVT(O), AVT(R), OT and on an amine treatment program.
    - It is essential that further knowledge is gained about the distribution of liquid at various positions in the duct, at the tube entries and at the entry to the vertical risers.
3. Laboratory studies: Once a quantitative understanding of the environment is developed then this can be used to develop laboratory equipment to simulate and thus understand the key factors involved in the corrosion/FAC process. These types of FAC (if indeed it is FAC) laboratory experiments are extremely difficult to develop and are not inexpensive. Perhaps some current apparatus can be modified to work at the low temperatures associated with ACC.
4. Test evaluations of various possible solutions could be done in a parallel effort in the laboratory and in the field. This might involve coatings [14], tube inserts, new tube materials, new chemistries (including amines),
5. A final step will be to develop a final chemistry guideline/guidance document for fossil units with ACCs using the field data already collected and the information from the suggested research.

Conclusion

Corrosion of carbon steel surfaces of ACC ducts and the upper condensing tubes is extensive in many cases. The corrosion tendencies appear to be independent of unit and ACC design. The damage results in excessive levels of iron transport when units with ACCs are operated in accordance with EPRI Cycle Chemistry Guidelines for units with water-cooled condensers.

At present there is insufficient information to fully define and confirm the damage mechanism. However, available results for damaged tube assessments points to a low temperature corrosion process, quite possibly flow-accelerated corrosion. Observed damage characteristics are inconsistent with an erosion mechanism.

Increasing the condensate pH to levels above those specified in the EPRI Guidelines has been demonstrated to significantly reduce iron transport in fossil units with ACCs. The benefits of operation at high pH have been corroborated at a number of power stations and a useful correlation of condensate iron and pH levels exists. When treating the cycle with ammonia to pH 9.8-10, condensate iron levels of ≤10ppb are generally achievable. The EPRI Interim Chemistry Guidelines for fossil cycles with ACCs were developed to take advantage of the demonstrated benefits of operation with increasing pH. They also indicate areas where users need to take care in customizing the guidelines to individual units. Several actions are available to those operating ACCs so as to minimize damage and transport of iron. A number of research activities could be taken to better understand conditions within the ACC are suggested.

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