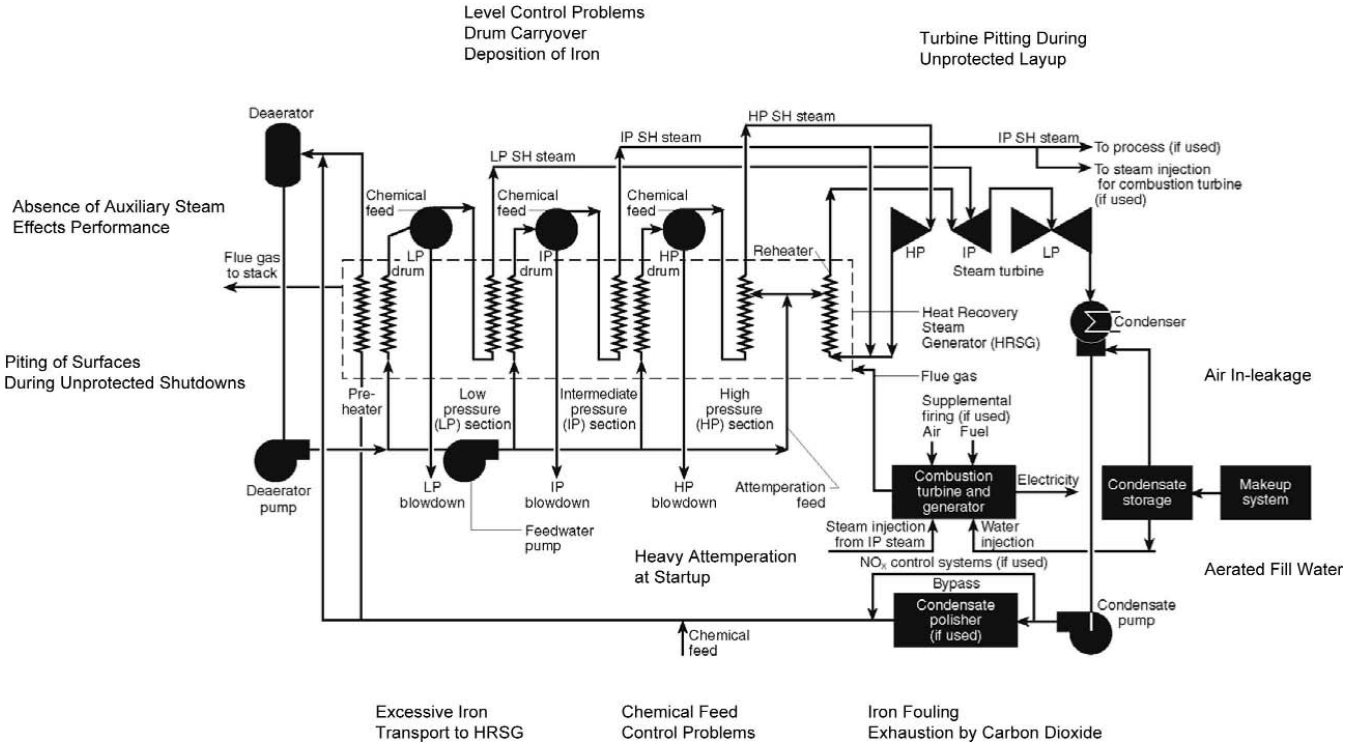
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Cycle Chemistry Guidelines for Shutdown, Layup, and Startup of Combined Cycle Units with Heat Recovery Steam Generators

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Cycle Chemistry Guidelines for Shutdown, Layup and Startup of Combined Cycle Units with Heat Recovery Steam Generators

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Final Report, March 2006

EPRI Project Manager
K. Shields

Electric Power Research Institute • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

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Electric Power Research Institute (EPRI)
3420 Hillview Avenue
Palo Alto, CA 94304

Authors
K. Shields
B. Dooley
A. Aschoff
M. Ball

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PRODUCT DESCRIPTION

Complete optimization of cycle chemistry in a combined-cycle unit requires more than proper selection and optimization of operating chemistry. Protection of the steam-water cycle also is essential during shutdown, layup, and startup phases. These guidelines consider protection of steam- and water-touched components at these times, consistent with the operating cycle chemistries in use.

Results & Findings

These guidelines have been developed specifically for use with *Cycle Chemistry Guidelines for Combined Cycle/Heat Recovery Steam Generators (HRSGs)* (1010438), the latest EPRI cycle chemistry guidelines for operating combined-cycle units with heat recovery steam generators.

Challenges & Objective(s)

Protection requirements are dependent on shutdown requirements. Four types of shutdown are defined, and users can apply these definitions as appropriate to the units they oversee. Short-term protection involves keeping the system hot and maintaining condenser vacuum; there is no need to change water chemistry while these conditions can be maintained. For longer shutdowns, there are three protection approaches that can be considered: dry protection with warm, dehumidified air; dry protection with nitrogen; and wet protection with a nitrogen cap.

Applications, Values & Use

The guidelines consider relevant experience from conventional fossil units as well as experience of combined cycle plant system and component providers and the early experience of organizations that operate these units. Use of effective protection methods is important in any generating assets but particularly so in those subjected to peaking service as is often the case with combined cycle units.

EPRI Perspective

The focal point of the guidelines is the three guiding principles of equipment protection, as defined in Section 2 of the report. The guiding principles can be used with all suitable operating chemistries, which should be selected and optimized as outlined in *Cycle Chemistry Guidelines for Combined Cycle/Heat Recovery Steam Generators (HRSGs)*. The guiding principles for equipment protection reflect the findings of EPRI research in protecting steam- and water-touched surfaces in fossil units. By applying these guiding principles and the protection options outlined in the report's road map and discussion, users may select and customize shutdown, layup, and startup practices that will meet the unique needs of their units.

Approach

EPRI and EPRI consultants familiar with cycle-chemistry guidelines development and associated equipment protection requirements and approaches conducted the project. The project team contacted major suppliers to become familiar with their approaches and also considered the experience of Program 88 members.

Keywords

Heat recovery steam generator
Chemistry
Shutdown
Layup
Startup

ABSTRACT

Combined cycle units with heat recovery steam generators offer great flexibility in that they can be shut down and placed in service very rapidly in comparison to conventional fossil units. Operating experience has indicated that many of the common causes of component damage and ensuing availability losses are directly or indirectly related to chemistry practices in use during shutdowns. The trend in many parts of the world toward increased operation of these assets for cycling and peaking service is likely to exacerbate the situation.

In many instances, the practices and procedures followed during combined cycle unit operations are deficient in that they do not provide satisfactory levels of protection to the water and steam touched components comprising the cycle during shutdown periods. Assessment of the basic science pertinent to off-line corrosion has resulted in identification of three essential guiding principles that must be considered when assessing the specific shutdown, layup and startup requirements of these units. These guidelines are the first of their kind. They introduce the guiding principles and show operating personnel how they apply during assessment activities for specific unit characteristics and operating requirements.

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The authors of these guidelines

K. Shields, EPRI
B. Dooley, EPRI
A. Aschoff, Consultant
M. Ball, Consultant

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A. Bursik, Consultant
D. Swainsbury, Consultant

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1
INFLUENCE OF SHUTDOWN, LAYUP AND STARTUP PRACTICES ON COMBINED CYCLE UNIT AVAILABILITY AND RELIABILITY

1.1 Cycle Chemistry Management Philosophy

Meeting operational water chemistry requirements in conventional fossil plant cycles is generally recognized as a key part of ensuring satisfactory levels of unit availability and reliability. Further, it has been observed that deterioration of equipment performance occurs when the chemistry is not optimized. In recognition of the influence of cycle chemistry on the unit, considerable effort has been expended to establish operating cycle chemistry guidelines. Many organizations have successfully implemented these guidelines.[1-3] Subsequent chemistry program benchmarking, EPRI Cycle Chemistry Improvement Program Workshops and chemistry value assessment activities have all demonstrated the benefits of applying and following the guidelines.

Many of the benefits possible with effective chemistry programs for feedwater and boiler water during normal operation may be diminished in the absence of effective chemistry control during idle periods. In many cases little or no attention is given to protection of equipment while the unit is out of service. Establishment of the optimum chemistry under all conditions has been an integral part of EPRI's philosophy for management of cycle chemistry in fossil units. A guideline dedicated to cycling, startup, shutdown and layup was published in 1998.[4]

This early work concentrated on fossil cycles with conventional boilers. The emergence of a worldwide fleet of combined cycle units with heat recovery steam generators (HRSGs) represented a significant change in design and operation relative to conventional units. Chemistry management philosophies and guidelines developed for conventional plant cycles are not entirely applicable to combined cycle units, the features and characteristics of which offer unique challenges to operators and chemists.

1.1.1 Cycle Chemistry Guidelines for Combined Cycle Units with HRSGs

Interim cycle chemistry guidelines for combined cycles with HRSGs were introduced by EPRI in 1998.[5] as the initial product developed as part of EPRI efforts to establish the HRSG Dependability Program. Work on the first revision of these guidelines was initiated in 2004 with the final report issued in 2005.[6]

The 1998 interim guidelines focused primarily on operational cycle chemistry needs; they considered the science on which guidelines for conventional cycles were based and unique characteristics and requirements of combined cycle units. They were developed to address a multiplicity of chemistry related failures and damage incidents that were being reported by combined cycle plant personnel; these include:

- Evaporator carryover and steam turbine damage
- Several types of HRSG tube failures (HTF)
  - Flow-accelerated corrosion (FAC) damage in feedwater systems, economizers and low pressure (LP) evaporators
  - Underdeposit corrosion in high pressure (HP) evaporator tubing by three mechanisms (hydrogen damage, acid phosphate corrosion and caustic corrosion)
  - Corrosion fatigue
- Corrosion during HRSG shutdown and idle periods

Investigation and evaluation of these early events concentrated on damage to steam turbines and HRSG tube failures since such events will have the greatest impacts on unit availability. In the case of evaporator carryover and turbine damage, it was found that several factors could be involved. HRSG design and operating practices were often deficient, resulting in episodes of carryover and transport of contaminants to the steam turbine. In many instances, the unit did not include the instrumentation needed to allow early detection of carryover problems. Performance testing of steam purity and related unit commissioning activities were apparently not able to identify conditions that could lead to future problems in all cases. In developing the interim chemistry guidelines for combined cycle plants, these incidents underscored the need for proper selection of the chemistry for feedwater and individual evaporator circuits, as well as the importance of steam drum mechanical carryover as a chemistry monitoring parameter. These aspects have been given far greater emphasis in the latest revision of the cycle chemistry guidelines.[6]

EPRI investigations of numerous HRSG tube failure incidents in various combined cycle unit configurations confirmed that many of the tube failure mechanisms are essentially identical to those observed in boilers of conventional cycles. However, responsible root causes and suitable corrective actions for HRSG tube failures by these otherwise common mechanisms may deviate from the experience with these mechanisms in conventional boilers. To address these deficiencies as well as address tube failure mechanisms unique to HRSGs, a tube failure manual was developed and published in 2002.[7] It was also determined that many HRSG tube failures resulted from deficient designs and that avoidance of such failures would thus be possible in future units. These findings were presented in a report that addressed important aspects of ensuring reliable HRSG delivery.[8]

Initially, less emphasis was placed on corrosion during HRSG shutdown and idle periods, since steam turbine damage and operational HRSG tube failure problems were of greater immediate concern. Also, prior to increases in fuel prices in many markets, it was not unusual for combined cycle units to operate under longterm power supply contracts. Thus it was quite common to

operate many if not most combined cycle units for extended periods with minimal shutdowns for purposes of economy.

The interim cycle chemistry guidelines for combined cycle plants with HRSGs included a section on shutdown and layup considerations that reviewed the techniques and procedures generally regarded as appropriate for conventional fossil plant units.[5] Past and present equipment protection practices available for combined cycle units are quite consistent with those developed for use in conventional units. The authors of these revised guidelines assessed industry practices and confirmed that there has been very little innovation on the part of equipment manufacturers and operators in this regard. It was also determined that there is considerable interest in establishment of equipment protection techniques that would offer operators more flexibility than the traditional methods.

1.1.2 Chemistry Selection and Optimization

Many chemistry related problems in conventional fossil units relate to improper selection of feedwater and boiler water chemistry. In some instances, incorrect choices were made initially, while in other, the significance of changes in unit design and operation on choice of chemistry were not recognized. The latest EPRI chemistry guidelines for conventional plants[1-3] provide clear direction in chemistry selection and stress the importance of periodic reassessment of the changing needs of the unit.

A similar approach is needed in combined cycle units and this is one of many improvements incorporated within the first revision of the cycle chemistry guidelines for combined cycle units with HRSGs.[6] Such efforts will be most effective in combined cycle unit designs that properly consider the operational chemistry requirements[8] and in units that evaluate the chemistry transients to avoid damage during the commissioning period and early operations.[9]

Complete optimization of the chemistry requires more than proper initial selection and periodic reassessments of the operating feedwater and evaporator water treatments. It requires that the chemistry environment be considered with provisions made to ensure that it is monitored and controlled as needed. This is often overlooked or neglected during idle periods such as maintenance shutdowns, when attention is normally directed to other important outage activities such as repairs, testing and inspections. Depending on the specific work to be done, some compromises in equipment layup may be needed. Unfortunately, it is also very common to provide unsatisfactory protection of the equipment during economy outages when no work needs to be done but uncertainties with respect to the duration of the shutdown period or the time required to return the unit to service may exist.

1.1.3 Peaking and Cycling Duty

For reasons of economy, it may be necessary to operate many combined cycle units in the peaking mode and/or subject to load cycling when in service. Many of the early high pressure designs assumed that the units would be operated primarily under essentially baseload conditions. The most serious consequence of this has been the high incidence of fatigue type

failures, due to more frequent thermal transients. [8, 9] Additional consequences relate to the fact that the cycle chemistry is more difficult to maintain, especially if it was not selected properly initially. Thus corrosion protection during shutdown and startup may not be adequate; deficient layup practices can further compound the problem.

1.1.4 Protection of the Steam-Water Cycle during Idle Periods to Prevent Equipment Damage

The protective oxide layers formed on water and steam touched surfaces during normal service operation cannot be maintained during idle periods unless appropriate steps are taken to control the chemistry environment. Unfortunately, chemistry control during shutdown periods is not always consistent with those practices known to protect steam generator tube waterside and steamside surfaces and surfaces of other combined cycle components from corrosion. Deficient chemistry practices during unit shutdown, layup and startup are either directly responsible for or a contributing factor to many HRSG waterside tube damage and failure mechanisms. Further, such deficient practices may have negative impacts on unit performance. Other non-chemical aspects of fossil unit shutdown and startup are also important as these can have influence on some HRSG tubing damage mechanisms, most notably thermal fatigue, irrespective of the chemistry practices followed.

Current industry practices with respect to protection of fossil units were captured as part of a survey of the worldwide community of water chemistry specialists, as part of a survey on cycle chemistry in fossil generating units conducted in 2003.[10] In conventional fossil plants, survey participants indicated that:

- Only 45% nitrogen blanket boilers during shutdowns
- Only 18% provide protection to reheaters during shutdowns
- Only 12% provide protection to steam turbines during long outages
- Only 11% nitrogen blanket feedwater heaters during shutdown

Although clearly far from desirable, these figures on equipment protection actually represent a slight improvement over results of earlier surveys of fossil plant chemistry personnel on this subject.

When asked to indicate their most serious cycle and chemistry problems, survey participants often indicated concerns which either typically or at least may in some instances involve the chemistry environment maintained during idle periods as well as operational cycle chemistry surveillance and control. These include:

- Turbine Deposits-Copper and Other (23%)
- Boiler Tube Failures by Corrosion Fatigue (22%)
- Boiler Tube Failures by Hydrogen Damage (14%)
- Feedwater Heater Corrosion and Transport (15%)

- Iron and Copper (12%)
- Condenser Leaks (49%)

These results fall far short of the EPRI cycle chemistry program goal stating that the cycle chemistry will be effectively managed and optimized under all operating conditions. When considering these statistics it quickly becomes clear that nearly every cycle component in contact with water and steam can be affected if satisfactory protection is not available. Furthermore, most of the organizations involved in the survey were not giving their generating assets the off-line protection needed to maximize their performance.

Although this survey included conventional fossil units, many of the responding organizations also operate combined cycle units with HRSGs. In view of this, there is reason for concern that many combined cycle units may ultimately exhibit a similar pattern. This concern is particularly acute in the case of units initially designed for baseload operation that now operate as peaking and cycling units due to present day economics governing dispatch of generating units. The HRSGs in these units are often subject to thermo-mechanical fatigue damage and may not have the facilities needed to support frequent shutdown/layup/startup requirements. In recognition of the importance of establishing combined cycle unit designs that facilitate operating practices and design features that support protection of the equipment during shutdowns EPRI developed the previously mentioned publication that focused on delivery of high reliability HRSGs.[8]

1.2 Effects of Deficient Shutdown, Layup and Startup Practices

The acts of removing a unit from service, maintaining it idle for various time periods and returning it to operation produce substantial chemical and thermal transients, which are potentially detrimental to the HRSG and other components of the steam-water cycle. Figure 1-1 identifies some possible consequences of deficient control of the chemistry at these times.

As with the operational chemistry, the chemistry during shutdown and layup must be effective in prevention of contaminant ingress and transport and of corrosion product formation and transport to areas where deposition will occur. In addition to contamination by dissolved solids and gases such as oxygen and carbon dioxide, outages represent a situation where other contaminants may be introduced to the cycle as a consequence of maintenance and inspection activities. Examples include grit blast media and other abrasives, paints, solvents and preservatives, cleaning chemicals, ambient dust and dirt, etc. It should be self-evident that during every outage where the steam-water cycle components will be opened that it is essential to have good accountability for materials and their usage and to practice good housekeeping practices. Also, making a final examination and, if needed, removal of foreign material prior to filling equipment with water for startup is very desirable as it can save much more time than it requires.

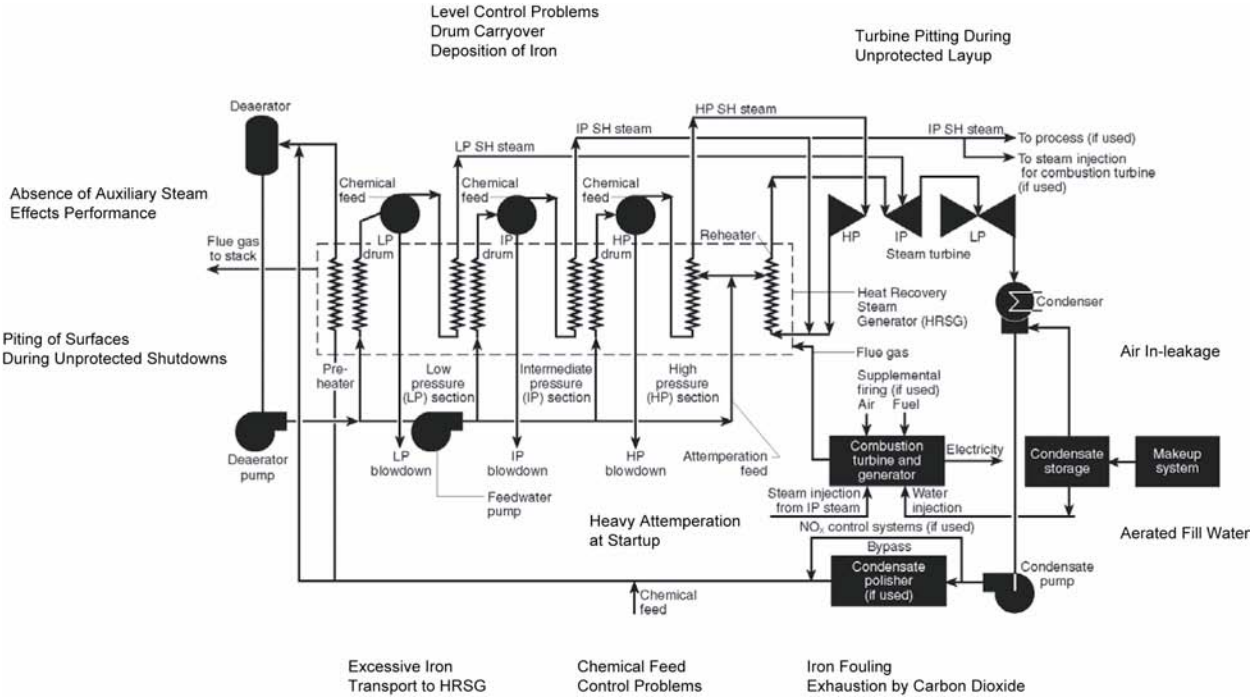


Figure 1-1
Possible Effects of Deficient Shutdown, Layup and Startup Practices in Combined Cycle Units

The effect most commonly experienced is loss of the protective oxide structure formed on water and steam touched surfaces during normal operation, pitting and general corrosion of unprotected surfaces during the idle period, and transport of metal oxides into the HRSG during the ensuing startup. Condenser air removal and thermal deaerator performance are often deficient during shutdown and startup periods, and these systems normally represent points of air (and oxygen) ingress while the unit is idle. Failure to exclude air during the shutdown often serves to minimize the effectiveness of protective layup measures.

The makeup water supply is often saturated with dissolved oxygen and carbon dioxide. While this is not optimal for normal service operation, it is unaccetptable as fill water for startup of equipment. Starting the unit up with oxygen saturated water invites further corrosion and subsequent oxide transport. In cases where the water supply is saturated with oxygen or is exposed to air (and oxygen) while in storage, improvements are desirable to remove oxygen prior to introducing it to the unit.

Startup operations must avoid chemistry excursions related to improper chemical dosing, condensate polisher (where available) operations and HRSG blowdown. Care must be taken to avoid steam contamination by means of excessive spray attemperation or carryover from drum type evaporator circuits. Drum level surveillance and control is especially important to avoid mechanical carryover of boiler water with saturated steam during startup. Sampling systems and on-line analyzers should be placed in service as soon as possible to allow timely identification of contamination during the startup.

1.2.1 HRSG Tube Damage

In 2002, EPRI completed the first and only comprehensive assessment of all aspects of tube failures in the HRSGs.[7] Damage mechanisms active in HRSGs are often analogous to those experienced in conventional boiler tubing; however there are frequently important differences in the underlying root causes, which will require unique corrective actions.

Discussion of the individual tube failure mechanisms of Reference 7 indicates that deficient shutdown, layup and startup practices may be involved.[7, 11] Three chemistry related mechanisms are very likely to be active or become active in the future in HRSGs if the unit shutdown, layup and startup practices are deficient:[7]

- Pitting, Figure 1-2
- Acid Dew Point Corrosion, Figure 1-3
- Corrosion Fatigue

Pitting attack will occur at surfaces exposed to moisture and oxygen under stagnant conditions. Proper layup protection of idle units prevents pitting. Acid dew point corrosion is influenced by the fireside environment and metal temperatures; corrosion may be exacerbated during steam generator shutdown. Corrosion fatigue is a complex mechanism, with both environmental and mechanical influences. It is active during all operating modes. Proper layup is crucial since breakdown of the protective oxide layer as a result of pitting during unprotected shutdown influences the mechanism.

The following underdeposit mechanisms are active entirely or at least mainly during normal HRSG operation, mainly in high pressure evaporator circuits.

- Hydrogen Damage, Figure 1-4(a)
- Caustic Corrosion, Figure 1-4(b)
- Acid Phosphate Corrosion, Figure 1-4(c)

Hydrogen damage, acid phosphate corrosion and caustic corrosion cause failures in drum type evaporators. These mechanisms are influenced by shutdown, layup and startup practices in that they either require or are enhanced by accumulation of waterside deposit materials. Deposit material is transported to the steam generator with the feedwater; transport is most significant during startups, especially when cycle equipment has not been protected during the outage.

In the case of designs where water from the low pressure (LP) or intermediate pressure (IP) is used as supply to the high pressure (HP) circuit, flow-accelerated corrosion (FAC) represents another source of iron oxide (Figure 1-5). Proper selection of the cycle chemistry essentially eliminates single phase FAC and may reduce the extent of two-phase FAC. For optimal control of FAC, it is important to maintain the same chemistry environment (oxidizing) at all times. A commonly observed deficient protection practice involves addition of wet layup treatments (reducing agents) that alter the chemical environment and will not provide optimal resistance to FAC.

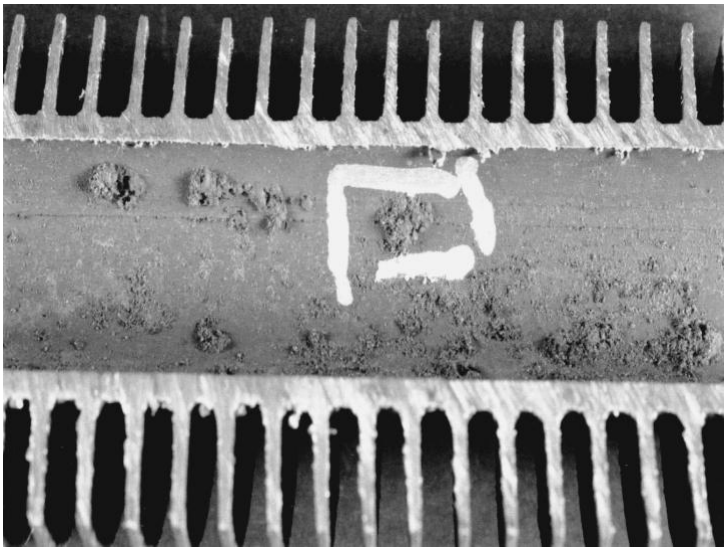
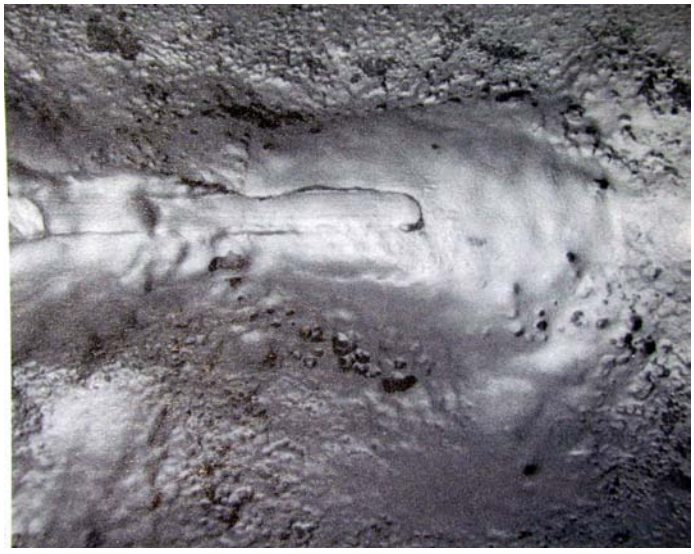


Figure 1-2
Pitting in HRSG Evaporator Tube [7]



Figure 1-3
HRSG Economizer Tube Fin Damage Caused by Acid Dewpoint Corrosion [7]

(a) 

(b) 

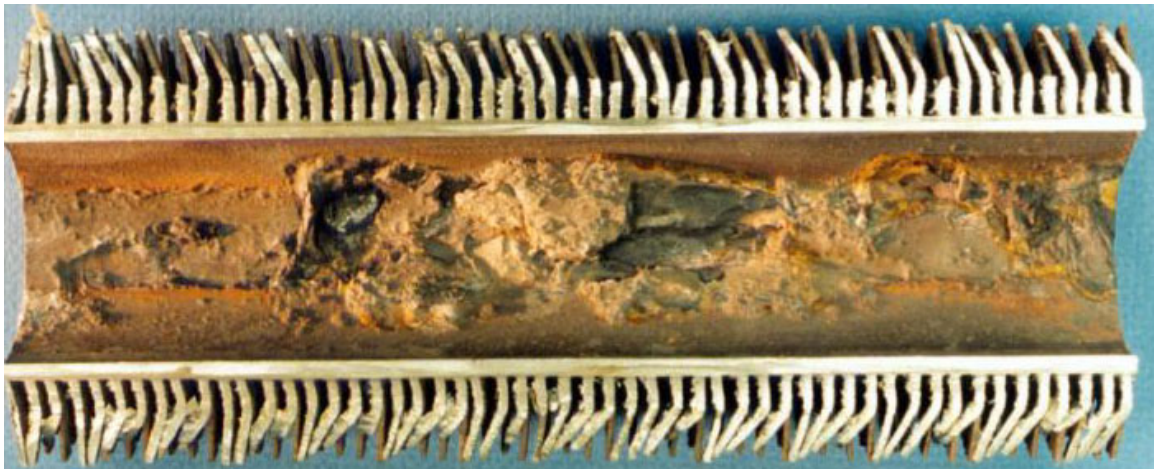
(c) 

Figure 1-4
Examples of Underdeposit Corrosion Damage: (a) HRSG HP Evaporator Tube with Hydrogen Damage; (b) Conventional Boiler Waterwall Tube with Deposits Removed to Show Caustic Corrosion Damage; (c) HRSG HP Evaporator Tube with Acid Phosphate Corrosion Damage[7]

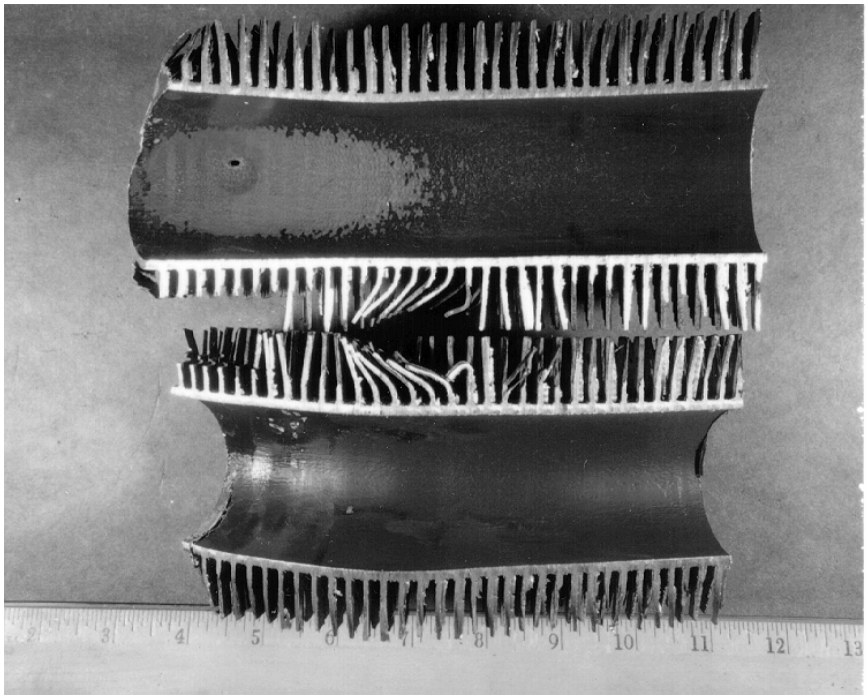


Figure 1-5
Flow-accelerated Corrosion Damage in Low Pressure Evaporator Tube [7]

1.2.2 Effects of Shutdown, Layup and Startup on Other Combined Cycle Unit Components

The increased likelihood of future HRSG tube failures are but one possible consequence of deficient shutdown, layup and startup practices. However, such deficient practices can affect other equipment in the cycle. Possible detrimental effects include:

- Pitting and general surface corrosion of water and steam touched surfaces in condensers, external deaerators, headers and piping, and steam turbines
- Deposition of corrosion products on evaporator feed pumps, in feedwater preheaters, in evaporator economizer and waterwall tubing, in once-through evaporator circuit orifices, in blowdown systems and on steam turbines
- Corrosion of the turbine in the presence of moisture, oxygen and salt deposits; such damage is often a precursor to future corrosion fatigue and stress corrosion cracking failures
- Exfoliation of steam path oxides resulting in solid particle erosion of steam turbines
- Hideout and return of impurities and treatment chemicals
- Increased thermal stresses, strain, and vibration
- Contamination of the steam-water cycle by equipment and material used during maintenance activity

Most of these concerns can be ameliorated through the same sort of diligence needed during unit shutdown, layup and startup periods to minimize the risk of HRSG tube damage. In fact, it is now clear that the most effective protection strategies are those that address the entire steam-water cycle. Perhaps the best example of this is the feedwater corrosion products that enter the HRSG and form deposits on evaporator tube waterside surfaces. These deposits increase the risk of on-line underdeposit corrosion (by hydrogen damage, acid phosphate corrosion or caustic gouging), shorten the interval between chemical cleans, and possibly reduce cycle efficiency.

1.2.2.1 Protection of Steam Turbines

It was indicated earlier that carryover to the steam turbine has been experienced during the commissioning and early commercial operation of many combined cycle units with HRSGs. Research investigations of stress corrosion cracking (SCC) and corrosion fatigue (CF) in steam turbines have determined that damage by these mechanisms typically initiates at micro-pits in the passive surface layer formed while the turbine is in service. During unprotected outages, pitting attack can break down this protective surface oxide layer. A schematic representation of the influences of turbine operation and turbine shutdown is shown in Figure 1-6. A deterministic model is being developed by EPRI to define the conditions leading to damage by these mechanisms more precisely. Pit growth and onset of SCC or CF are dependent on operating conditions; however, these mechanisms cannot become active if the requisite precursor conditions associated with unprotected shutdowns are avoided. The latest research clearly suggests that protection of steam turbines during all outages is essential to avoiding the developments of micro-pits that are the precursors to cracking via SCC and CF.[13, 14] Field experience has shown that use of dehumidified air is an effective means of preventing accumulation of moisture and/or liquids on turbine surfaces during the shutdown and layup periods. Following this approach reduces the risk of developing pitting, corrosion fatigue and stress corrosion cracking in turbine disks and blades.

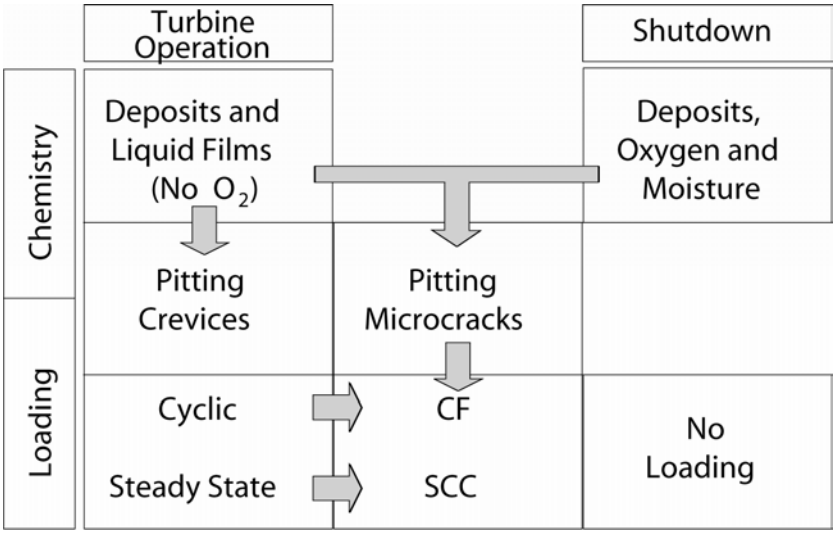


Figure 1-6
Schematic Showing Influence of Turbine Operation and Shutdown on Corrosion Fatigue and Stress Corrosion Cracking[13]

1.3 Chemistry Guidelines for Shutdown, Layup and Startup

1.3.1 Purpose and Approach

The primary purpose of these guidelines is to make operators of combined cycle plants aware of the importance of protecting cycle water and steam touched surfaces of plant components during idle periods and of available and effective techniques and practices that can support equipment protection. The approach taken is to establish guiding principles applicable to all cycle designs, treatment approaches and operational requirements. Suitable methods consistent with these guiding principles for protection of combined cycle units are identified and discussed. Road maps are introduced to enable operators to evaluate and select suitable approaches consistent with the guiding principles and specific unit characteristics. Determination of the specific optimal requirements for implementing effective protection of individual units is beyond the scope of these guidelines; users must perform such assessments and initiate the correct actions, including engineering of solutions, on a case by case basis. This process includes monitoring to evaluate the efficacy of the protection practices in use.

1.3.2 Guidelines Overview

Subsequent sections of this guidelines document focus on specific aspects of off-line protection of steam and water touched surfaces of combined cycle units. Section 2 presents background information on corrosion damage in unprotected equipment and establishes the guiding principles that must be adhered to in order to prevent such damage. Section 2 also identifies and discusses important factors that operators of combined cycle units must consider when evaluating equipment protection needs, and developing implementation strategies. General considerations of unit shutdown and protection methods are presented in Section 3, along with an overall road map illustrating the approach to be followed. Shutdown considerations specific to the various evaporator water chemistries are discussed in Section 4. Return of combined cycle units to service following shutdowns is the subject of Section 5; discussion of the startup is based on chemistry-specific concerns for each of the evaporator treatment options available.

1.3.3 How to Use these Guidelines

These guidelines are intended to be used in combination with properly selected and optimized feedwater and evaporator water treatments, which are described in a separate EPRI document, *Cycle Chemistry Guidelines for Combined Cycle Heat Recovery Steam Generators (HRSG), Revision 1*.[(6)] Users desiring to evaluate their shutdown, layup and startup practices should first ensure that the chemistry in use has been properly selected and optimized. The user should then consider the guiding principles for equipment protection and consider current and anticipated future unit operating requirements, outage characteristics and unit design aspects, as addressed in Section 2. Within this framework, the guidelines of Sections 3 through 5 may be reviewed to determine suitable approaches based on the guiding principles that may be further customized as needed for effective chemistry control during combined cycle unit shutdown, layup and startup.

Additional information is included in three report appendices. Appendix A discussed some alternative equipment protection approaches which rely on establishment of barrier films on the surfaces to be protected. Appendix B discusses options for removal of dissolved oxygen from cycle makeup water. Measurement and control of cycle air inleakage during startup and normal operation is the subject of Appendix C.

1.4 References

1. Cycle Chemistry Guidelines for Fossil Plants: All-volatile Treatment, Revision 1. EPRI, Palo Alto, CA: 2002. 1004187.
2. Cycle Chemistry Guidelines for Fossil Plants: Phosphate Continuum and Caustic Treatment. EPRI, Palo Alto, CA: 2004. 1004188.
3. Cycle Chemistry Guidelines for Fossil Plants: Oxygenated Treatment. EPRI, Palo Alto, CA: 2005. 1004925.
4. Cycling, Startup, Shutdown and Lay-up Fossil Plant Cycle Chemistry Guidelines for Operators and Chemists. EPRI, Palo Alto, CA: 1998. TR-107754.
5. Interim Cycle Chemistry Guidelines for Combined Cycle Heat Recovery Steam Generators (HRSGs). EPRI, Palo Alto, CA: 1998. TR-110051.
6. Cycle Chemistry Guidelines for Combined Cycle/Heat Recovery Steam Generators (HRSGs). EPRI, Palo Alto, CA: 2006. 1010438.
7. Heat Recovery Steam Generator Tube Failure Manual. EPRI, Palo Alto, CA: 2002. 1004503.
8. Delivering High Reliability HRSGs. EPRI, Palo Alto, CA: 2003. 1004240.
9. Diagnostic/Troubleshooting Monitoring to Identify Damaging Cycle Chemistry or Thermal Transients in Heat Recovery Steam Generator Pressure Parts. EPRI, Palo Alto, CA: 2005. 1008088.
10. Survey Results, Proceedings: Seventh International Conference on Cycle Chemistry in Fossil Plants: June 3-5, 2003, Houston, Texas. EPRI, Palo Alto, CA: 2004. 1009194.
11. K. J. Shields and A. F. Aschoff, “Influence of Steam Generator Shutdown, Layup and Startup Chemistry Control Practices on Steam Generator Tube Failures”, Proceedings: Boiler Tube and HRSG Tube Failure and Inspection International Conference: November 2-4, 2004, San Diego, California. EPRI, Palo Alto, CA: 2004. (Publication pending.)
12. Heat Recovery Steam Generator (HRSG) Chemical Cleaning Guidelines. EPRI, Palo Alto, CA: 2003. 1004499.
13. Corrosion of Low Pressure Steam Turbine Components. EPRI, Palo Alto, CA: 2000. 1000557.
14. Development of Code to Predict Stress Corrosion Cracking and Corrosion Fatigue of Low Pressure Turbine Components. EPRI, Palo Alto, CA: 2004. 1004190

2
APPROACH TO GUIDELINES DEVELOPMENT AND CUSTOMIZATION

2.1 Introduction

Effective protection of steam and water touched components of fossil plant cycles must consider the relevant science (Section 2.2). Further, protection strategies must be validated by successful field operating experience. Guiding principles for equipment protection are outlined in Section 2.3. Conformance with the guiding principles is considered essential when evaluating, selecting and applying the available choices proven effective for equipment protection, as covered in Section 3. Sections 4 and 5 present chemistry-specific concerns for start-up of heat recovery steam generators (HRSGs) with the various evaporator design and chemical treatment combinations.

Experience has shown that a number of equipment protection strategies exist, consistent with the guiding principles, that are effective for equipment protection in conventional fossil plant cycles and thus considered suitable for use in combined cycle units. These strategies are discussed in detail in Section 3. Applicability of established equipment protection measures and selection of the optimal approach is dependent on many factors. These include the type of outage (Section 2.4) and other factors specific to the unit (Section 2.5). The need to customize the guidelines for optimal use in individual combined cycle units is discussed in Section 2.6.

Two methods of equipment protection of possible interest, mainly for extended protection based on establishment of barrier films on surfaces, are identified and briefly discussed in Section 2.7; further information is included in Appendix A.

2.2 Protection of Water and Steam Touched Surfaces

Upon determining that a combined cycle unit is to be removed from service, the chemistry environment within the steam-water cycle must be considered and adjusted as needed to ensure suitable protection of all steam and water touched surfaces until such time as the unit is back in service. Different approaches exist and may be suitable depending on local conditions and unit operational requirements. Irrespective of these issues the applicable science that influences equipment protection are the same.[(1)] Thus the unit must be removed from service, placed in a protective layup condition that supports return of the unit to service with minimal impact on water chemistry and the condition of surface oxides formed during normal unit operations. The transitions between periods of operation must provide adequate protection under all conditions that may be encountered until the unit is restored to service. From a cycle chemistry perspective,

passage through such transitions should be approached as a seamless, continual process, as opposed to discrete steps. For example, a layup procedure that allows ingress of ambient air prior to implementation is likely to be very ineffective relative to a procedure that minimizes such ingress under all operating conditions.

Simply stated, the purpose of layup is to protect the steam and water touched surfaces of equipment comprising the steam-water circuit from corrosion while the combined cycle unit is not generating power. Corrosion may take the form of pitting attack or as the more widespread breakdown of the protective metal oxide surface layer formed during service.

Materials of construction influence the feedwater chemistry selection as well as the approach to layup. In combined cycle units, the vast majority of surfaces comprising the steam-water cycle are comprised of ferrous materials. Based largely on unfavorable experience in conventional plant cycles and changes in the relative cost of materials over time, most combined cycle units include little or no copper based materials in water and steam touched components. The tubing of water cooled surface condensers is a possible exception but even here, materials such as stainless steels or titanium are usually the preferred choice.

2.2.1 Protection of Steels

In normal service with proper chemistry conditions, a protective oxide layer is formed on steel surfaces in contact with water and steam. Disruption of the protective oxide layer will occur during unprotected shutdowns. Corrosion will occur when surfaces are in contact with moisture or stagnant water that contains dissolved oxygen. Thus when wetted surfaces are to be maintained wet, it is crucial to both exclude oxygen ingress and avoid stagnant conditions.

It is quite common for some water to be retained following draining of plant equipment. Condensation of moisture on previously dry surfaces as a consequence of typical ambient air temperature and humidity variations will occur under most climate conditions. Retained water on surfaces and surface moisture formed as consequence of normal condensation can lead to attack on the protective surface oxide when in contact with ambient air, which serves as a source of oxygen.

Stagnancy should be regarded as a prerequisite condition for the inception of pitting in steels at wetted surfaces when oxygen is present. Thus the protection of steel surfaces during shutdown requires that either: (1) contact with moisture and water is avoided or (2) wetted surfaces are denied access to oxygen in air and the water is circulated to avoid stagnant conditions.

Pitting of metals is a complex subject. The phenomenon of attack on steels in aerated stagnant water is common to many industries and well understood. Features of pitting damage on steels are quite distinct.[2] For example, pits can either be numerous and closely spaced, or isolated. They are often covered with caps of corrosion products. An example of pitting in an HRSG evaporator tube is provided in Figure 1-2. The pits are typically filled with corrosion products, particularly red hematite iron oxide (Fe_2O_3) which is the thermodynamically favored reaction product of iron with oxygen under conditions of high oxygen activity. This form of pitting may undercut the surface.

Figure 2-1 displays a cross-sectional view through an oxygen pit that was filled with corrosion products and covered by a distinctive corrosion cap.

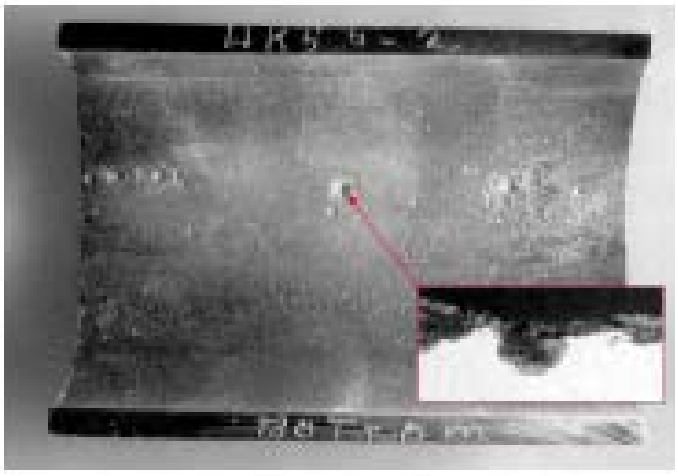


Figure 2-1
Cross Section through a Pit Showing Corrosion Product Cap and Corrosion Products in the Pit

Experience in HRSG units has documented the development of pitting damage. Affected locations include feedwater heaters and preheaters, economizers, and evaporators. However, superheaters and reheaters are also viewed as susceptible to pitting damage. Horizontal tubing is particularly vulnerable to pitting if not fully drainable and not provided with a protective environment during the shutdown periods. Other component surfaces, particularly those composed of carbon steel are susceptible to pitting attack if proper shutdown and layup practices are not used.(2)

Pitting corrosion can produce damage and failures in a variety of components, materials and aqueous environments. Pitting is considered a likely precursor to other damage mechanisms including corrosion fatigue and stress corrosion cracking. Accordingly, it has been the subject of extensive research and development. As a result of these activities, the complex nature of the pitting process has become well understood. Various modeling studies, in combination with other research, have helped to determine how pits develop and identified the important environmental parameters that influence the mechanism.

It cannot be overemphasized that the key feature to note is that pitting only occurs during unprotected shutdown periods, and not when the unit is operating. During shutdown, the remaining water is often left stagnant and steel surfaces left open to the atmosphere. Under these conditions, the residual water (or moisture condensing on surfaces) becomes saturated with oxygen.

Pitting and other related localized corrosion processes such as crevice corrosion involve selective breakdown of the passive films normally present on the metal surface. The environment will affect pitting activity and severity. Chloride ions, for instance, are well known for causing chemically induced breakdown of the passive layer, which results in pitting corrosion. As an

example, improper chemical cleaning with hydrochloric acid often results in severe pitting attack. However, impurities such as chloride, if present in the water can also exacerbate pitting damage during unprotected shutdowns.

Other anions besides chloride have been determined to be capable of attacking the passive film. For example, dilute sulfate solutions can lead to pitting in reheaters and in the low pressure section of steam turbines of conventional fossil units. These pits exhibit distinct differences from pitting which can develop in relatively pure water normally present in the steam-water cycle during shutdowns.[2]

The pitting corrosion process can be considered to consist of two stages: pit induction (i.e., the time to first pit formation, also termed "initiation" or "nucleation") and subsequent growth. Pits tend to initiate at surface irregularities such as dislocations, grain boundaries, or locations of non-metallic inclusions.[3] For example, sulfide inclusions in austenitic and ferritic stainless steels have been shown by many investigators to be favored initiation sites.[4-8] Pit shape and density depend on the crystallographic orientation of the surface exposed.[3]

Breakdown of the passive film can occur for several possible reasons and three types of models have been proposed to describe the pitting initiation process[4]:

1. Adsorption and adsorption-induced models in which the adsorption of aggressive anions like chloride is central
2. Ion migration and penetration models
3. Mechanical film breakdown models

The point defect model (PDM)[3, 9] proposed by Macdonald, *et al.*[10, 11] provides an explanation for the stages of pit nucleation as shown schematically in Figure 2-2. This figure shows the steady state growth condition where a passive film grows on the metal surface. In the steady state condition, the rates of film formation at the metal/film interface and the rate of film dissolution at the film/solution interface are in balance (Figure 2-2a).[9] Transport of metal ions through the oxide film occurs. However, if the film growing at the film/metal interface is disrupted (Figures 2-2 b and c) subsequent straining or dissolving of the partial film can lead to rupture (Figure 2-2 d). One means by which the film can be broken down according to the PDM, is by the condensing of cation vacancies arriving at the metal/film interface, that is, by generation of more cation vacancies at the film/solution interface than can be absorbed at the metal film/interface. When the voids reach a critical size, the passive film collapses leading to pit growth.

The steps shown in Figure 2-2 a-d can be considered the nucleation stage of pitting with either subsequent re-passivation or pit growth by dissolution of the metal (Figure 2-2 e).

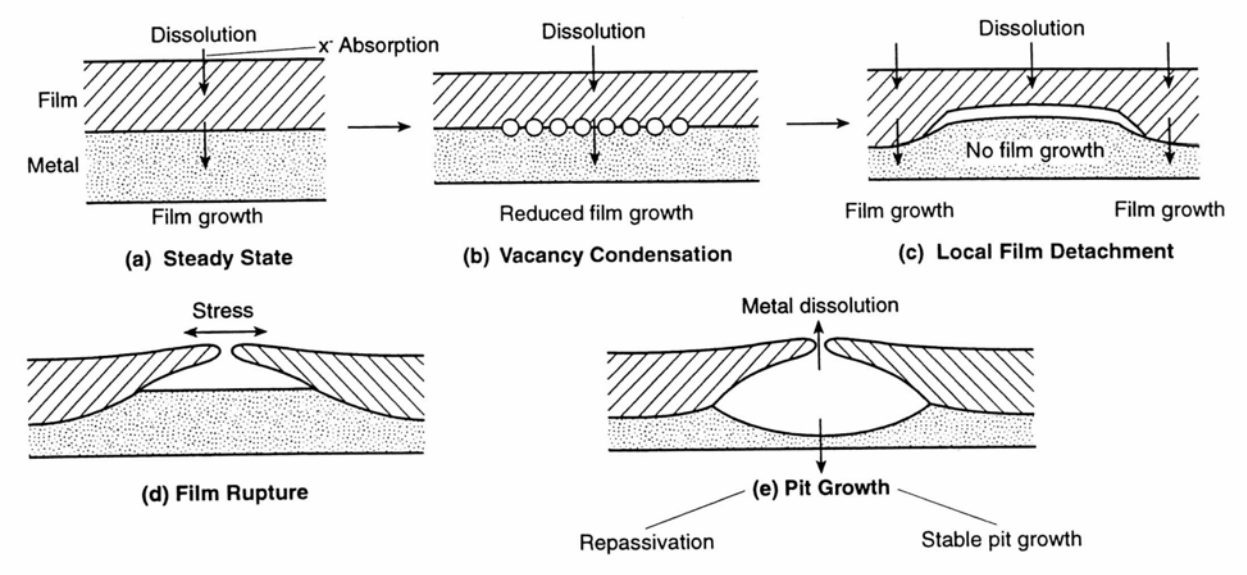


Figure 2-2
Schematic Outlining Various Stages of Pit Nucleation According to the Point Defect Model
Source: Reference 9

In cases where the pitted surface does not re-passivate, corrosion within the pit (pit growth) can be rapid and essentially independent of the external environment.

Pit growth is considered to be an autocatalytic process: the environment within the pit supports the continued activity of the corrodent. In HRSG tubing, for example, deposition of corrosion products and anions in the water (chloride, sulfate, etc.) support initiation of pitting. High levels of dissolved oxygen, as exist during unprotected unit shutdown, layup and startup periods, serve to make metal surfaces more susceptible to pitting corrosion. Pitting is most prominent under stagnant conditions. The fact that the fluid is static allows the initiation of pitting to occur unimpeded. Stagnant conditions allow for the concentrations needed to accelerate the attack. Once initiation has begun (such as during an unprotected shutdown of the unit) then continued growth of the pit will occur during each unprotected shutdown. These pits can also initiate cracks during operation; this is of particular concern in steam turbines especially if the surfaces were contaminated during service. However, pitting can occur even during normal steam turbine operation as a consequence of impurity concentration effects within the liquid films present on surfaces within the phase transition zone (PTZ).

The interface of the remaining fluid with the environment is a particularly corrosive area. Thus the air water interface in components maintained wet without nitrogen blankets or, in drained components, any remaining accumulations of water such as in tubing or piping u-bends or on horizontal surfaces are areas which are extremely prone to pit initiation and growth.

Pit growth is often influenced by gravity, which accounts for the susceptibility of horizontal surfaces to attack. The formation of a dense, concentrated solution and its retention favors the propagation of the pit, a process that is facilitated if the pit is oriented downward, to the pull of gravity.

2.2.2 Protection of Copper Alloys

As stated previously, use of copper alloys in the feedwater part of combined cycle units is not common. Nevertheless, some combined cycle units may include some copper in the feedwater system though the surface area of copper in combined cycles is likely to be very low relative to that present in conventional cycles. Also, combined cycle units with all ferrous feedwater metallurgy may utilize copper alloys in the condenser.

Research conducted under EPRI's Program Copper demonstrated that satisfactory protection of copper alloys in the feedwater of conventional cycles under typical operating conditions requires that a reducing environment (with a reducing oxidation-reduction potential) be established and maintained).[12-15] Failure to continue to provide a reducing environment during shutdown, layup and startup is very disruptive to the protective oxide layer of cuprous oxide, Cu_2O and would result in significant copper transport activity. However, it should be kept in mind that the reducing environment favorable to copper is known to exacerbate flow-accelerated corrosion (FAC) damage in steels; a 2004 survey determined that FAC was the most prevalent HRSG tube failure (HTF) damage mechanism.

Copper alloy condenser tubes, on the other hand, exist in an oxidizing environment at all times (even when the feedwater part of the plant operates in a reducing environment) and are subject to low operating temperatures as compared to feedwater heaters. Thus it is possible and advantageous to utilize oxidizing chemistries in cycles with all ferrous feedwater systems of combined cycles even if a copper alloy is selected for the condenser tubes.

2.3 Guiding Principles Governing Protection of Cycle Components During Shutdown, Layup and Startup

Operating experience, as reflected in the survey results of fossil plant chemistry personnel presented in Section 1[16], makes it clear that efforts to protect equipment during outages is often unsatisfactory. It is also apparent that some of the serious problems chemistry personnel face involve the shutdown/layup/startup period. Further, it is clear that many steam generator tube failure mechanisms, both chemical and non-chemical, are influenced by the operating practices followed at this time. The research activities of EPRI continue to yield findings supporting these observations and confirming that it is very important to maintain a protective chemical environment during fossil unit shutdowns.

In view of the foregoing, it becomes apparent that operators of fossil units need to place greater emphasis on equipment protection during shutdowns. The objective of such action is to eliminate pitting and general surface corrosion as this will maintain the stability of protective metal oxides formed during normal operation. Successful implementation of equipment protection serves the

broader purpose of minimizing damage by other mechanisms which are active when the unit is in service.

Guiding Principles for protection of fossil plant equipment, developed by EPRI and based on worldwide experience including EPRI's application of an integrated HTF reduction program and cycle chemistry program, need to be kept in mind when addressing chemistry control during unit shutdown. These guiding principles are applicable to both combined cycle units and conventional fossil units.

In order to avoid damage to water and steam touched surfaces of cycle components during shutdown and layup periods a seamless transition from service through the shutdown, during the time out of service (protected layup) and the subsequent startup to return the unit to service is needed. The science of corrosion during idle periods is well understood and clearly points to the following Guiding Principles which, if considered in unit operating practices and procedures will prevent damage:

1. Keep the Potential of Water in the Cycle the Same During All Operating Conditions.

This requires:

- When using oxidizing all-volatile treatment (AVT(O)) or oxygenated treatment (OT) as the feedwater treatment, not adding reducing agents during shutdown, layup or at startup, and actively keeping air out of the cycle.
- When using reducing all-volatile (AVT(R)) feedwater treatment, keeping the potential reducing by keeping reducing agent in the water during shutdown and actively keeping air out of the cycle.
- With all feedwater and evaporator water treatments, operate as needed to comply with Guiding Principle 2.

It should be noted that, for combined cycle units, the preferred feedwater treatment is AVT(O). Treatment selection criteria for feedwater and evaporator water are provided in EPRI's cycle chemistry guidelines. [18]

2. Keep Water from Becoming Oxygenated by the Surrounding Environment.

This requires:

- Avoid air ingress during shutdown by maintaining condenser vacuum as long as possible.
- Keep oxygen out of water during layup by nitrogen blanketing. The nitrogen system should have multiple entry points to ensure all pressure circuits are covered.
- Avoid stagnant, oxygenated water conditions, which can lead to pitting corrosion; a small circulation of the fluid will prevent the stagnant conditions.
- Use high purity water of low oxygen content to fill equipment prior to startup and as cycle makeup during the startup. This will entail using a nitrogen sparging system in the storage

tank, use of a gas transfer membrane or elevating the temperature of the water in the storage tank.

- Use auxiliary steam at startup to prevent air ingress at deaerators during startup.

3. Keep Water and Moisture out of Steam Touched Components and any Water Touched Surfaces to be Maintained Dry during the Shutdown Period.

This requires:

- Use of warm dehumidified air to protect steam turbines (particularly the LP turbine) and reheaters.
- Rapid draining of normally water touched components while they are still hot; this will result in flashing of residual water prior to dry layup or activities such as equipment inspection or maintenance.

The operator should regard each unit shutdown as a unique event. A means of equipment layup effective in protecting all water and steam touched surfaces must be implemented by the operator; layup practices must consider and be consistent with unit design and operation, but also be in line with the Guiding Principles.

Protection of cycle steam and water touched surfaces is important during both planned and unplanned shutdowns. The Guiding Principles must become a key part of the plant operation procedures. For example, equipment inspection, repair and maintenance requirements, when applicable, will vary and must be accounted for when implementing equipment protection procedures, but in all cases the Guiding Principles are of paramount importance. Shutdowns involving such activities require special attention; further action may be needed before transitioning the unit from the shutdown to the layup condition. Under all circumstances, transition to the layup condition must be seamless, particularly if wet layup is to be used.

Similarly, when evaluating new shutdown and layup procedures or returning to service from an unusual outage condition the Guiding Principles must be thought of first. Such an example might be after a chemical cleaning. In all cases it is necessary to monitor cycle chemistry during startups and initial unit operations as needed to assess the adequacy of the equipment protection measures during the shutdown.

The optimal protection strategy for a particular unit will naturally depend on site-specific factors. These include unit design and operational requirements. The strategy will also need to consider the requirements of the outage and its expected duration. Regardless of the specific requirements, the Guiding Principles outline the general requirements applicable in virtually all circumstances that operating personnel should adopt when determining the best strategy to employ in individual combined cycle units.

2.4 Unit Outages and Shutdowns

Successful protection strategies to be followed should always consider the guiding principles for equipment protection. They should also consider the purpose of the outage and the expected duration of the shutdown period.

Optimal equipment protection during outages will typically depend on the nature of the shutdown and the purpose of the ensuing outage.

Most shutdowns (including shutdowns for economy) are of an elective nature; they typically occur with some advance notice and usually offer at least some flexibility in timing and should thus be controllable by the operators of the unit. The shutdown should be initiated with equipment protection in mind, even if the duration of the outage is uncertain. Unless there is a specific need to work on the equipment and there is assurance that the shutdown duration will allow it, opening of equipment is generally not practiced during economy outages.

Unplanned shutdowns that are forced due to reasons such as mechanical problems in the plant, severe water chemistry excursions, loss of connection to the grid or other causes occur with little or no advance notice and may restrict the ability of the operator to control the shutdown. Circumstances will determine the nature of the ensuing outage, and it is frequently necessary to open equipment for inspection and repairs. However it is still important to plan for protection of all water and steam touched surfaces comprising the cycle.

Outages are required for various reasons. Depending on cost of power from competing sources, economy is often a common reason for outages in combined cycle units. Outages may be needed for short term action such as repairs of mechanical equipment or initial resolution of component damage such as evaporator or water cooled condenser tube leaks. Longer outages are typically needed in instances where more extensive repairs are required, including off-site repairs, and for scheduled major maintenance and inspection activities.

The guidelines for layup presented in Section 3 look at short term, intermediate term and longterm layup, as well as the protection requirements of extended outages. These guidelines consider both the duration of the outage and the purpose. Determination of the most suitable approach to equipment protection must be made at the plant level, in consideration of the guiding principles for equipment protection, the choices for layup outlined in Section 3 and specific needs of individual units.

2.4.1 Short Term Outage

Short term outages may be defined as outages during which oxygen can be excluded from the system and temperatures can be maintained high enough to avoid condensation on surfaces and facilitate flashing of liquid on surfaces if the cycle should need to be drained. In many combined cycle units it is not possible to maintain condenser vacuum for more than about 24 hours after shutdown; the most common application of short term protection applied to overnight shutdowns. The duration can be extended somewhat if the condenser steam space and steam turbine can be protected by introduction of dehumidified air (preferred) or nitrogen. Use of

nitrogen to blanket other parts of the cycle as temperatures fall and pressures decrease is also desirable. Steam blanketing of equipment, where possible and affordable, also helps to both exclude oxygen and maintain temperature during the outage.

2.4.2 Intermediate and Longterm Outages

Outage protection needs change when it is no longer possible to maintain satisfactory short term protection; operators of combined cycle units need to recognize the capability and limitations of individual systems and define the boundary between short term and longer term outages accordingly.

Intermediate term protection becomes necessary when short term protection is no longer practical or possible. A typical duration would include weekend shutdowns and outages of up to about five days.

Longterm protection methods are typically effective for several days or even a few weeks as needed; this period is dependent on several factors and proper monitoring is needed to assure that the protection remains effective. Continuation of intermediate outage protection measures may be effective. With longer anticipated outage durations, more reliable protection may be expected through use of dry layup procedures.

2.4.3 Extended Outages

Organizations operating in markets with low power costs, and high generating capacity may elect to consider extended protection covering several weeks when operation of their combined cycle unit assets is not economically competitive. Protection may well be possible through continuation of longterm or even intermediate protection measures. In all cases protection measures applied should effectively address all of the guiding principles of Section 2.3.

The strategies presented in Section 3 of these guidelines address only the water and steam touched surfaces of the steam-water cycle in detail for the above outage conditions. Some general guidance is provided with respect to protection of other areas of combined cycle units.

2.4.4 Outages Requiring Plant Mothballing Protection

In some cases protection of plant equipment could be needed for many months or possibly years and consider equipment and systems beyond the boundaries of the steam-water cycle. These guidelines are not intended to cover situations where mothballing of units will be required as a long range strategy.

2.5 Unit Design Factors Influencing Combined Cycle Unit Shutdown, Layup and Startup

Many aspects of the unit design will influence shutdown, layup and startup. Ensuing discussions review the more common factors, emphasizing their influence on corrosion, corrosion product transport, and other cycle chemistry effects.

2.5.1 HRSG Tubing and Gas Path Arrangement

While designs that employ horizontal gas paths and vertical tubing are most common (Figure 2-3), HRSGs with vertical gas paths and horizontal tubing (Figure 2-4) are also in use. With either arrangement, all heat input may be derived entirely from combustion turbine (CT) off gases, or from a combination of CT off gases and firing of supplemental fuels in duct burners.

Circulation pumps are not normally provided on horizontal gas path designs but may be included in vertical gas path designs. Circulation capability can be advantageous for wet layup protection of the HRSG as it will help in compliance with the second guiding principle..

2.5.2 Evaporator Circuit Design

While most evaporator circuits are of the drum type, there are a few HRSGs with once-through circuits; most of these units are in North America. Some designs include a drum type low pressure (LP) circuit, while in others this circuit is also of once-through design.

In selection of cycle chemistry, each evaporator circuit must be considered as a separate system, while also considering the needs of rest of the HRSG. Combined cycle units can be placed in service very rapidly and thus it is crucial during startup to monitor drum levels and carryover carefully. Otherwise uncontrolled drum level increases could result in introduction of solids based chemicals (trisodium phosphate and caustic) to the saturated steam. Depending on sensitivity of the unit in question, it may be necessary to limit evaporator circuit dosing startup.

2.5.3 System Drains and Vents

Drains are sometimes undersized or arranged in a way that inhibits complete draining of steam-touched circuits at startup. This can result in blocked tubes which contribute to thermal stress and fatigue type damage and failures as is discussed extensively in other EPRI publications.[2, 17] Drain connections on water touched circuits can serve as a bottleneck and may inhibit the ability to drain these circuits quickly and completely while the metal is still hot. Based on experience in conventional boilers, it seems likely that horizontally tubed circuits will likely be slower to drain and more difficult to drain completely than vertically tubed circuits. Draining and venting characteristics can have direct bearing on compliance with each of the three guiding principles.

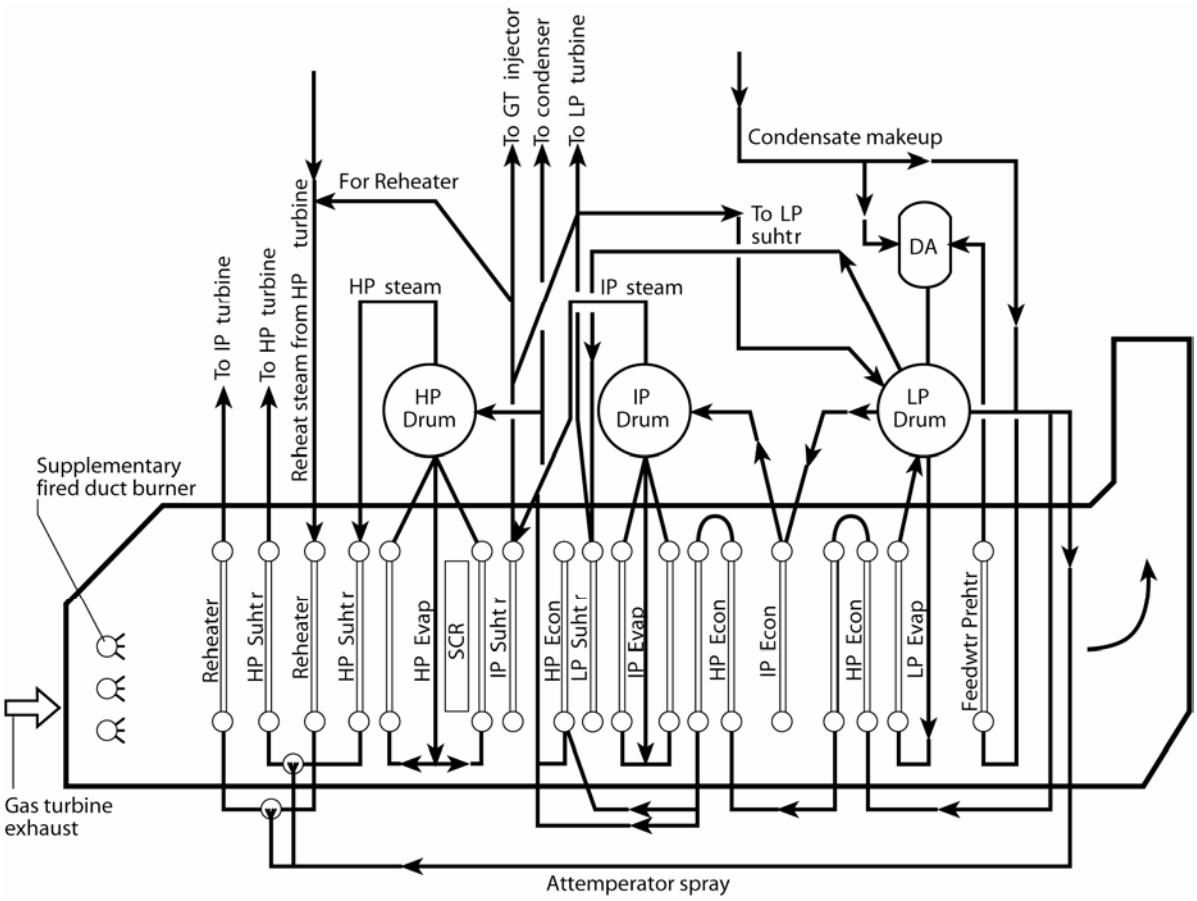


Figure 2-3
Natural Circulation, Vertical Tubed, Multi-pressure HRSG[2]

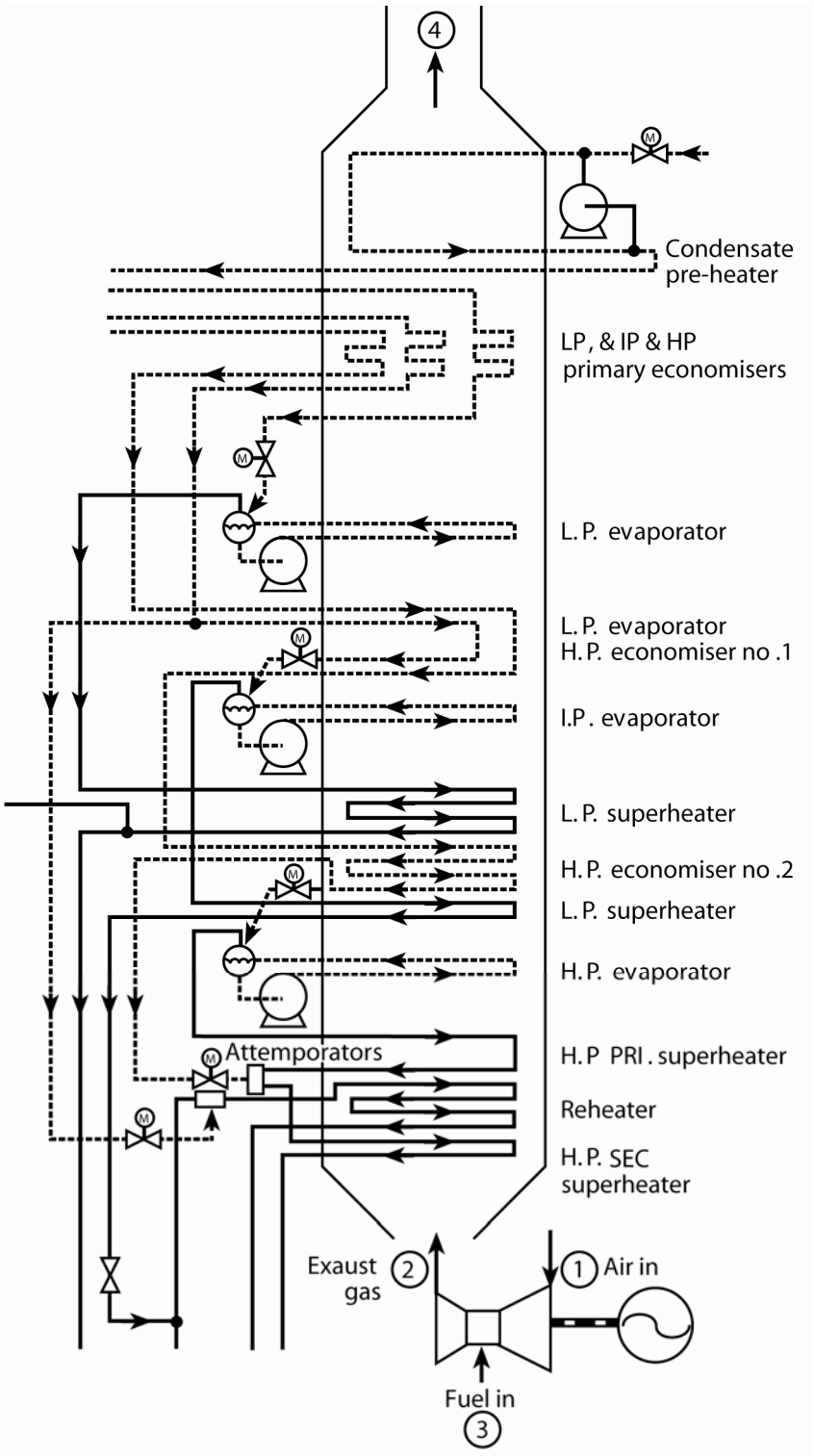


Figure 2-4
Horizontal Tube Typical Configuration for Drum-type HRSG[2]

2.5.4 Materials of Construction

Cycle materials will have direct bearing on the method of layup selected; further discussion is provided in Section 2.2 and in Section 3.1.2 of these guidelines.

2.5.5 Cycle Chemistry

The guidelines of Sections 3, 4 and 5 reflect the choice of operating feedwater and evaporator circuit chemistries. As discussed earlier, the choice of the feedwater treatment (almost always AVT(O)) is dependent on cycle materials, which has direct implications on wet layup treatments since the chemistry environment (potential) should be constant during all operating conditions. As clearly indicated in the first guiding principle, the potential should not be allowed to drift between oxidizing and reducing conditions, meaning that use of reducing agents to protect systems operated with AVT(O) is not allowed.

Evaporator treatments can have implications on combined cycle unit startup. Solids based treatments such as phosphate continuum (PC) and caustic treatment (CT) offer possible benefits in avoidance of corrosion fatigue damage at startup. Their use at startup is also beneficial in the event undetected cycle contamination is present. However, these chemistries cannot be used in low pressure (LP) evaporator circuits that provide attemperation water to superheater and reheater circuits or when the LP evaporator supplies water to other evaporator circuits. Also, their use during startup could be problematic in drum circuits that are prone to drum swelling, sudden level increases and mechanical carryover during startups.

In older conventional cycles with drum boilers, use of solids based treatments was often preferred during unit commissioning, even if the intention is to use volatile chemistry during commercial service since cycle integrity is not known. However, in view of possible steam purity concerns, the opposite approach has actually been taken in some combined cycle systems.

In new combined cycle units that will be operated on solids based evaporator treatments in any circuit, it is sometimes considered prudent to conduct the initial operations during the commissioning of the HRSG with volatile chemistry until the sensitivity to carryover as a result of drum level increase at startup is known. Carryover testing of each circuit is regarded as mandatory during the commissioning period. Further, carryover is now an EPRI core monitoring parameter for normal operation.

In at least some cases, it will likely be found to be better to continue to start the unit up on volatile chemistry and introduce the solids based treatment at some minimum load that has been demonstrated to support stable control of drum level in the evaporator circuits. Operating procedures for unit shutdown should be made as needed to accommodate this approach. In others, it may be suitable to maintain the operating chemistry in the boiler during shutdowns where the HRSG is to be protected in a wet condition.

2.5.6 Turbine Bypass Systems

Turbine bypass systems are often installed on many newer combined cycle systems with reheater circuits as a means to minimize thermal transients. Another benefit is to establish suitable steam purity prior to closing the bypass. Use of bypass systems also minimizes the risk of steam turbine damage by oxides and foreign objects; however, it should be recognized that any solids entrained in the steam when the bypass is open will enter the condenser.

2.5.7 Condensate Polishers and Filters

Condensate polishing is not available on most combined cycle units; the main exceptions are some units with either once-through evaporators or air cooled condensers. Use of these polishers, where provided, can help clean up the cycle during unit startup. However, conducting unit shutdown, layup activities in accordance with the guiding principles of Section 2.3 will serve to reduce the need for cycle cleanup during startup.

Polishers allow for both dissolved solids capture via ion exchange and filtration of metal oxides. Filtration capability is particularly beneficial in units with air cooled condensers as there is often high iron transport, especially during early service operations and during unit startups. Polishers and filters are worth considering as part of the design of any combined unit but offers greatest value in units that are subject to peaking service operation.

Typically, units with these systems will include recirculation lines to maximize cleanup early in the startup. Units with polishers and steam bypass systems are also well suited to cleanup of the condensate as part of the startup process.

2.5.8 Condenser Air Removal and Feedwater Deaeration Capabilities

The latest EPRI cycle chemistry guidelines recognize the importance of controlling condenser air in-leakage and reducing dissolved oxygen at the condensate pump discharge to <10 ppb.[18] Attainment of this criterion requires that air in-leakage be well controlled, particularly at locations beneath the water level in water cooled condensers. The air removal system must be sized to quickly establish vacuum at startup and also capable of maintaining the condensate system under vacuum until other equipment protection measures (dehumidified air, nitrogen blanketing or auxiliary steam blanketing) can be implemented. Such capabilities are integral to compliance with the second guiding principle. Further discussion of this important subject is included in Appendix C.

2.6 Application of These Guidelines to Individual Combined Cycle Units

As indicated in the previous discussion, there is a multiplicity of factors that will influence the chemistry during shutdown, layup and startup. Many of these factors can influence the effectiveness and even the applicability of the choices that must be made for shutdown and layup of combined cycle units, as outlined in Sections 3 and 4. It is thus quite clear that no guidelines or road map could adequately address all possible plant designs, operating requirements, outage

conditions, etc. Determination of the optimum approach to shutdown, layup, and startup must be consistent with the guiding principles of Section 2.3 for equipment protection. This assessment and customization approach will result in detailed procedures and, where needed, engineering solutions that best meet the needs of the individual unit. Practices and procedures which deviate from the guiding principles (or simply taking no action at all to protect the cycle) will inevitably lead to the various problems presented earlier with unavoidable losses in unit availability and performance.

2.7 References

1. K. J. Shields and A. F. Aschoff, "Influence of Steam Generator Shutdown, Layup and Startup Chemistry Control Practices on Steam Generator Tube Failures". *Proceedings: Boiler Tube and HRSG Tube Failure and Inspection International Conference: November 2-4, 2004, San Diego, California,* EPRI, Palo Alto, CA: 2004. (Publication pending.)
2. Heat Recovery Steam Generator Tube Failure Manual. EPRI, Palo Alto, CA: 2002. EPRI 1004503.
3. H. Bohni, "Pitting and Crevice Corrosion", in M.O. Speidel and A. Atrens, eds., *Corrosion in Power Generating Equipment*. Plenum Press. New York, 1984, pp. 29-48.
4. P.E. Manning, *et al., Corrosion,* 38, 1980, p. 313.
5. J. Degerbeck, *Werst. Und Korrosion, 29,* 1978, p. 179.
6. M. Henthrone, *Corrosion, 26,* 1970, p. 511.
7. Z. Szdarska-Smialowska, *et al., Br. Corr. J.,* 5, 197, p. 159.
8. B.R.T. Anderson and B. Solly, *Scand J. of Metallurgy*, 4, 1975, p. 85.
9. D.D. Macdonald, "The Point Defect Model for the Passive State", *Journal of the Electrochemical Society,* Volume 139, No. 12, February, 1992, pp. 3434-3449.
10. C.Y. Chao, L.F. Lin, and D.D. Macdonald, *J. Electrochem. Soc.*, 128, 1981, p. 1187.
11. L.F. Lin, C.Y. Chao, and D.D. Macdonald, *J. Electrochem. Soc.*, 128, 1981, p. 1194.
12. State-of-Knowledge of Copper in Fossil Plant Cycles. EPRI, Palo Alto, CA: 1997. TR-108460.
13. *Guidelines for Copper in Fossil Plants.* EPRI, Palo Alto, CA. EPRI 100457**.** November 2000.
14. Copper Alloy Corrosion in High Purity Feedwater: Admiralty Brass, Aluminum Brass, and 90/10 Copper/ Nickel at 95°C (203°F). EPRI, Palo Alto, CA: 2003. 1007391.
15. Influence of Water Chemistry on Copper Alloy Corrosion in High Purity Feedwater. EPRI, Palo Alto, CA: 2003. 1007612.

16. Survey Results, Proceedings: Seventh International Conference on Cycle Chemistry in Fossil Plants: June 3-5, 2003, Houston, Texas. EPRI, Palo Alto, CA: 2004. 1009194.

17. *Delivering High Reliability HRSGs*. EPRI, Palo Alto, CA: 2003. 1004240.

18. Cycle Chemistry Guidelines for Combined Cycle Heat Recovery Steam Generators (HRSGs), EPRI, Palo Alto, CA: 2006. 1010438.

3
SHUTDOWN AND LAYUP TECHNIQUES FOR WATER AND STEAM TOUCHED SURFACES OF COMBINED CYCLE PLANT COMPONENTS

3.1 Introduction to Shutdown and Layup of Combined Cycles

A review of the failure mechanisms in combined cycle plants[1-3] indicates that stresses and chemistry changes imposed by cyclic operation account for most of the damage to HRSG pressure parts. Unit startup and shutdown impose significantly more potential for damage than steady-state operation. Allowance for these conditions must be considered early in the design phase of the unit.

Two actions recommended during design are[1]:

- Develop detailed integrated unit startup, shutdown and operating procedures early in the design process, to be refined and confirmed during commissioning and operation.
- Design appropriate hardware and controls required to ensure proper ability to achieve the developed operating procedures.

In providing these actions, it is implicit that the design assessment should also assess the protection requirements that are likely to exist during commercial operation of the plant and consider systems and equipment that would be needed for effective layup.

There are only two major equipment design options available for conventional units, drum and once through, although there are many variables relative to pressures, temperatures and balance of plant equipment. The situation is much more complex in combined cycle design configurations. Combined cycle units include, at present, one to three separate pressure evaporator circuit designs and may include drum circuits, once-through circuits and combinations of drum/once-through circuits. Even though combined cycles are of increasingly complex design, the principles of layup, startup, and shutdown are similar to those used in conventional units and the guiding principles of Section 2.3 must be adapted and applied. However, some aspects of layup, startup and shutdown will need to be modified from the guidelines given herein to account for unique differences in equipment, design and operation vs. conventional units. For example, combined cycles may or may not include stand-alone deaerators; reheaters; and, a feedwater heater(s), among other differences; however, protection of steam and water touched surfaces based on the Section 2 guiding principles applies to all pressure values and cycle configurations.

A summation of important differences in actual HRSG configurations has been tabulated in a recent EPRI publication.[2] These include, but are by no means limited to the following:

- HRSG design concepts and details
- Single pressure, dual pressure, and multi-pressure designs
- Vertical and horizontal tube/flow designs
- Inclusion of reheaters is now common, but was not included in the design of most early operating units
- Natural circulation, assisted circulation, or forced circulation
- Drum or once-through evaporator circuits
- Balance of plant (BOP) design differences
- Supplemental (duct) firing
- Multiple fuel options
- Exhaust bypass and/or stack closure dampers may or may not be present
- Feedwater heaters/preheaters may or may not be present
- Selective catalytic reduction (SCR) for NO_X control and oxidation catalyst for CO abatement may or may not be present
- Water from the LP circuit may or may not be fed to IP and HP circuits
- Water from the IP circuit may or may not be fed to the HP circuit
- Cascade blowdown may be practiced on multiple pressure drum HRSGs
- Attemperation water may be taken from various sources
- Deaeration may be performed only in the condenser or using a deaerator in the feedwater system or LP circuit,
- Condenser may be water cooled or air cooled
- Condensate polishers may or may not be present

Therefore, because of the complexities of design inherent in today's combined cycles, it is impossible to address all procedural aspects of layup, startup and shutdown, which could be encountered in modern combined cycle design. The discussion which follows will concentrate on the general principles of this topic, assuming the individual operators will have enough information from the ensuing discussion to adapt the processes described herein to fit the equipment being operated.

3.1.1 General Layup Considerations

Flow accelerated corrosion (FAC) is perhaps the most important HRSG tube failure mechanism in combined cycle plants. A 2004 survey by EPRI determined it to be the ranked first by the

participants.[4] FAC is strongly influenced by the feedwater chemical composition, which benefits significantly through operation in the oxidizing mode, all-volatile treatment (AVT(O)) or oxygenated treatment (OT) as described in the recent EPRI publication "Cycle Chemistry Guidelines for Combined Cycle/Heat Recovery Steam Generators".[5] Operating in the AVT(O) or OT mode will reduce iron concentrations in the cycle and minimize the occurrence of single-phase FAC.

The alternate feedwater system is AVT(R) which requires the use of a reducing agent (hydrazine) in addition to a pH control chemical (ammonia). This system, which is mandatory for HRSG cycles with mixed metallurgy, is not required, nor is it desired for the all-ferrous feedwater systems (exclusive of the condenser tube materials) commonly used in combined cycles with HRSGs.

Since the vast majority of HRSG installations today utilize all-ferrous feedwater systems, and because of the advantages of operations in the oxidizing mode, it is the EPRI philosophy to use either AVT(O) or OT, rather than AVT (R) for HRSG feedwater systems with all-ferrous metallurgy (again excluding the condenser). Therefore, this document is focused primarily on all-ferrous units operated in the oxidizing regime.

The two types of layup applicable to all types of units, conventional and combined cycle, are classified as "wet" or "dry". For short term protection, it is generally permissible to simply keep the same water chemistry as during normal operation while taking measures to exclude oxygen such as keeping equipment hot and maintaining condenser vacuum. Wet layup for longer shutdown periods requires the filling of most of the system with an alkaline solution and preventing air ingress by pressurizing with nitrogen. The use of wet layup solutions in AVT(O) or OT units should generally be restricted to short term protection, since the guiding principles clearly indicate the use of hydrazine is not allowed wet layup solutions for units operated under oxidizing conditions. Extended wet layup without a reducing agent in these types of units will lead to pitting attack unless the equipment is reliably nitrogen capped and there is a means provided to periodically circulate the layup solution. In view of these concerns, dry layup methods are clearly preferred for all but short term protection of OT and AVT(O) units. (Wet layup of HRSG cycles with mixed metallurgy feedwater systems operating on AVT(R) involves filling applicable circuits with a solution containing ammonia and hydrazine and applying a nitrogen cap according to the duration of the shutdown.)

Dry layup requires draining the units while hot, and removal of all water followed by use of dehumidified air or pressurization with a moisture-free inert gas (nitrogen) to maintain a low moisture environment.

3.1.2 Shutdown, Layup and Startup of HRSGs with Multiple Evaporator Circuits

The HRSG will often include two or three evaporator circuits, operated at different pressures. While in some cases it may be possible to utilize a common evaporator treatment in each circuit, there are many instances where the chemistry selected should be different for the individual pressure stages. For example, in HRSGs with three drum evaporator circuits, a solid alkali is often added to the low pressure (LP) and possibly intermediate pressure (IP) circuits for FAC

protection where not prohibited by use of water from the LP circuit for steam attemperation. Users of these guidelines are referred to the revised HRSG Cycle Chemistry Guidelines for further details on chemistry selection and optimization.[5] Where different chemistries are in use, the shutdown, layup and startup practices to be followed should be selected accordingly as required by the guiding principles for equipment protection.

Ideally, the evaporator chemical conditions during shutdown and short term layup would normally be the same as during operation. However, care would be needed to ensure that during the ensuing startup, the chemical conditions (e.g. PC or CT) in one pressure stage (e.g. LP) do not adversely affect the chemical conditions in other pressure stages, for example through the use of water from one evaporator circuit as feedwater to another as is required in some designs. Of more widespread concern is the possibility of carryover in drum evaporator circuits during startups when using phosphate continuum or caustic treatment. These concerns are greatest during cold starts, when heating of the cold water will sometimes lead to swings in level in the drum circuits, possibly resulting in introduction of any solids in the evaporator water to the steam via mechanical carryover. Startup procedures for HRSG circuits containing solids based treatment chemicals must be alert to this possibility.

For longer shutdowns it will be necessary to change the chemistry, or preferably drain the circuits for dry layup protection. The shutdown discussions of Section 4 address shutdown for each of the available evaporator chemistries. The startup requirements for each evaporator circuit will still depend on the operating treatment applied; guidance is included in Section 5.

Carryover characteristics for each drum evaporator circuit should be carefully evaluated during unit commissioning and early commercial service under all startup and operational conditions. This is particularly important because combined cycle plants are placed in service rapidly and frequently include HRSG drum evaporator circuits with relatively small drums and simple steam separator devices, as compared to those present in conventional cycles with radiant drum boilers. To avoid the risk of steam path contamination by solids-based treatments during commissioning, some manufacturers have elected to place all circuits of the HRSG in service on AVT until pressures and drum levels have stabilized, at which time PC or CT treatment would be introduced, where allowable and desired. This approach would appear to be especially useful during cold startups of commercial units where level control problems have been experienced. Following this option could expose the HRSG to corrosion if the feedwater is contaminated so it is essential to carefully monitor the chemistry during the startup.

In summary, there are several factors that must be considered with respect to evaporator chemistry during shutdown, layup and startup of HRSGs with multiple evaporator circuits. When the HRSG features more than one evaporator stage, it is first necessary to consider the operating chemistry and treatment needs of each circuit through the selection and optimization process. Shutdown, layup and startup procedures must consider the treatments in use and the guiding principles for equipment protection. It is necessary to understand the startup characteristics of the unit and anticipate the startup conditions that will follow the shutdown. For effective chemistry management of drum evaporator circuits employing PC or CT, it is clearly important that the operator have a good understanding of the drum level and carryover tendencies. The shutdown

should be planned based on this knowledge, as well as the purpose and the expected duration of the outage.

3.1.3 Feedwater Systems Containing Copper

As mentioned in Section 2, the metallurgy of the feedwater system must be carefully considered when establishing chemistry parameters for startup, shutdown, and layup. As most combined units are designed with all ferrous feedwater systems, subsequent discussions are directed to protection measures for these cycles.

For the few combined cycle units with feedwater systems containing copper alloys, it is most important to maintain a reducing atmosphere (ORP < 0mV) at all times through operation with AVT(R). During operation this is generally accomplished by the use of suitable concentrations of hydrazine to establish reducing conditions and with addition of ammonia to regulate pH in the range of 9.0-9.3. The reducing environment must also be maintained during shutdown and layup periods. Oxygen ingress must be avoided, as this will increase the corrosion rate of copper alloys by changing the predominant surface oxide to cupric oxide.

The cycling of units, accompanied by periods of layup, materially increases the risk of copper alloy attack, because of the opportunities for oxygen ingress with associated increases of ORP into the oxidizing range. Therefore, chemistry control under these conditions requires much more attention than for baseloaded units.

The reader is referred to the HRSG cycle chemistry guidelines[(5)] for further discussion of mixed-metallurgy feedwater systems for combined cycle units operating with AVT(R) feedwater chemistry.

3.2 Roadmap for Selection of Layup Techniques for Use in Combined Cycle Units

A generic road map indicating layup procedures suitable following shutdown of combined cycle units is shown in Figure 3-1. Because of variations in design, some generating units may require deviations from this road map, or may require customization to adapt to a particular plant design as previously discussed. Figure 3-1 is divided into eight steps, which are further described as follows.

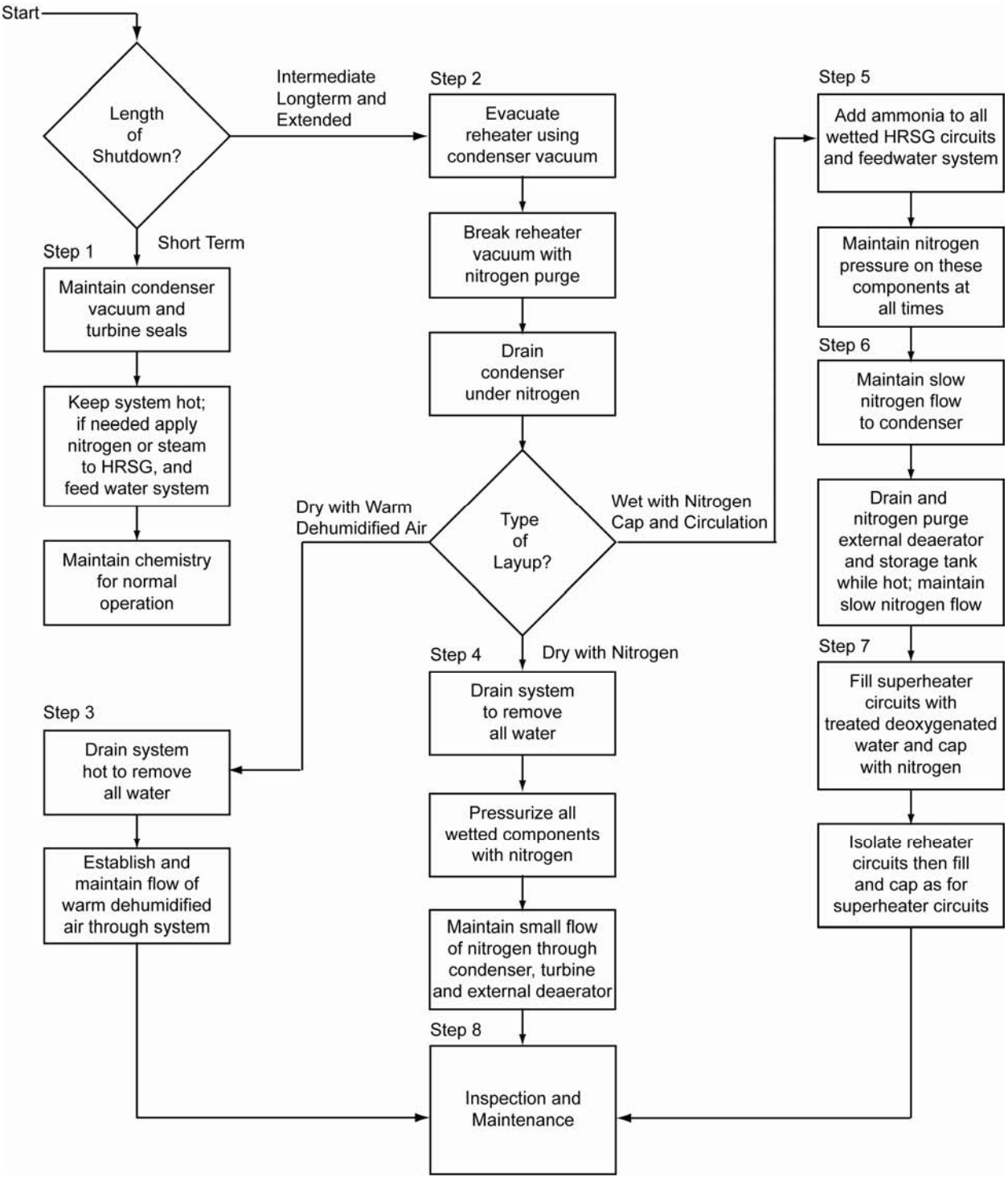


Figure 3-1
Road Map for Shutdown and Layup Guidelines Common to Most Combined Cycle Units

Step 1 – Short Term Shutdown

Short-term layup presumes that the unit will be required to operate within a relatively short time frame. Protection is based on the guiding principles that the potential of the water should be kept the same during all operating conditions. During short term shutdowns it is expected that the pressure will not decay to atmospheric which is consistent with the second guiding principle stating that the water should not be allowed to become oxygenated by the surrounding environment. Thus no major changes are required from normal operating conditions, with the exception being that the unit must be protected from air ingress. The condenser vacuum and turbine seals are maintained; and, the deaerator and heater shells (if provided) and HRSG are capped with nitrogen or steam. The feedwater chemistry is maintained according to the requirements of the AVT(O) or (OT) treatment employed.

If short term protection cannot be maintained before the units will be returned to service, it should receive protection suitable for a longer shutdown period.

Step 2 – Intermediate, Longterm and Extended Shutdown

Intermediate, longterm and extended shutdowns require additional steps to be taken to prevent corrosion during intermediate shutdown periods, such as for maintenance and indeterminate cycling or peaking requirements; and during longterm or extended shutdowns. Certain actions, described here, are common preparation requirements regardless of shutdown duration, and whether the unit is to be laid up dry (Step 3 or 4) or wet (Steps 5-7).

As the shutdown period increases there is a danger of off-load corrosion (pitting) if the water in any vessels or tubing becomes oxygenated. Thus a wet layup approach needs to carefully consider the requirement of the second guiding principle stating that the water must not become oxygenated and further that stagnant conditions should be avoided.

During shutdown, protection of steamside surfaces of the turbine, condenser and any reheater circuits are generally considered together because, unless special facilities are provided (most likely for an extended shutdown or mothballing) there is no practical way to isolate them. For Step 2, reheater circuits should be evacuated with the condenser still under vacuum. Nitrogen should be introduced for purging of the reheater and draining of the condenser. It is preferable to conduct the evacuation procedures at temperatures above ambient. For this reason, vacuum drying should be applied immediately after the unit is drained hot. An additional heat supply is advantageous.[(6)] Hot draining with subsequent vacuum drying should be also used if the dry layup will be applied after repairs to some pressure parts of the HRSG. If the unit is connected to any external steam sources, such as auxiliary steam systems, all isolation valves must be tight to prevent moisture entry into the unit during shutdowns. Again, these actions must be taken to avoid oxygenation of the water in accordance with the second guiding principle.

With special facilities incorporated, the superheater and reheater can be isolated from the turbine and may be stored wet (see Step 7 of roadmap). The turbine, however, can only be laid up dry. Utilization of warm, dehumidified air (Step 3) in accordance with the third guiding principle stating that water and moisture must be excluded from surfaces to be maintained dry is

considered the best approach to protection of these components. It is also considered a very useful approach for more widespread protection of the HRSG and other steam-water cycle components during shutdown periods. Protection of the turbine by a continuous nitrogen purge (Step 4) is another available option.

Step 3 – Dry Air Layup and Step 4 - Dry Layup with Nitrogen

The dry layup procedures require that all components of the system be drained and dried in accordance with the third guiding principle from Section 2.3 which requires elimination of water and moisture. Draining of water in steam-touched systems occurs at a residual pressure of up to 300 psi (about 2 MPa) depending on the configuration and the construction of the unit. Any remaining water in the entire system may be evaporated under vacuum using the unit evacuating equipment (e.g., evacuation of connected systems: feedwater line, heater(s) (if furnished), HRSG, main steam lines, HP bypass, cold reheat line, reheater, hot reheat line, IP bypass, condenser). Experience indicates that the circuits of many HRSGs are not designed for effective draining. Personnel responsible for equipment protection should be aware of this possibility and consider means to shorten the time and improve the thoroughness of drain procedures. If needed, these procedures can also be used during extended shutdowns.

For Step 3, Dried Air Layup, protection with warm, dry air layup requires that all components of the system be drained and dried quickly, in accordance with the third guiding principle, and maintaining dry air flow through the system. The intent is to reduce the relative humidity of the air in the equipment being protected to levels (<40 % and typically 30-35%) at which corrosion will not develop. Use of warm, dry air provides excellent protection during extended outages and is widely and successfully used for plant mothballing. The equipment required for dry layup is described later in this section, together with the advantages and disadvantages relative to wet layup protection.

Entry of protected equipment for inspection and maintenance is possible when employing dry layup with warm, dehumidified air. It is of course necessary to follow all relevant plant safety precautions that apply. To minimize the risk of moisture formation, points of access should be opened for the minimum time and to the minimum extent practical.

When selecting Step 4, Dry Layup with Nitrogen, nitrogen gas is used for blanketing equipment while and after it is drained; surfaces of protected surfaces do not need to be completely dry. Protection is obtained through conformance to the second and third guiding principles. After draining, nitrogen is applied to establish and maintain a positive pressure on all wetted components. A small continuous flow of nitrogen is required, however, to protect the turbine and deaerator tank (if furnished).

Step 5 – Wet Layup with Nitrogen Cap (HRSG Water Touched Circuits and Feedwater)

In accordance with the second guiding principle, a nitrogen cap of 5 psi (about 35 kPa) is maintained over wetted economizer and evaporator circuits of the HRSG and the feedwater system. The pH of the water may be raised with ammonia (at concentrations of up to 10 ppm) for longer wet layup periods. Ammonia addition may be made during the shutdown if a long layup is

expected. If not known before shutdown, draining and refilling will be required; the operation should be done under positive nitrogen pressure and deoxygenated fill water should be used. This approach should also be followed if it becomes necessary to drain these components for any reason.

Periodic (at least weekly) circulation of the wet layup solution is needed to help avoid pitting corrosion. In HRSG designs with circulation pumps, this pump can be used to provide circulation. Another approach is the use external pumps that permit continuous circulation of water in the HRSG circuits during shutdowns.

Step 6 – Wet Layup with Nitrogen Cap (Balance of Cycle)

As the turbine spins down, nitrogen is added to the condenser, which also purges the reheater system. A continuous purge of nitrogen is necessary to account for leakage through the turbine steam seals.

Nitrogen is added to the external deaerator and storage tank (in systems equipped with them) while this system is still hot. A small flow of nitrogen is provided to purge this system.

A nitrogen cap is maintained on the shell side of any feedwater heaters provided.

Step 7 – Wet Layup for Longterm and Extended Shutdowns

When using wet layup for longer storage periods, additional steps can be taken to protect the HRSG steam touched circuits. For longterm shutdowns superheater circuits may be filled with a solution of deoxygenated high purity water treated with (up to 10 ppm of) ammonia and a nitrogen cap is maintained. For extended shutdowns reheater circuits (when present) are isolated from the turbine and filled with a solution of deoxygenated high purity water treated with (up to 10 ppm of ammonia) and capped with nitrogen. Protection in this way is consistent with the second guiding principle of keeping the water from becoming saturated with oxygen. It is very important that the fill water used is deoxygenated (Appendix B) and that a means of reliable circulation should be provided as well.

Step 8 – Equipment Inspection and Maintenance

Equipment inspection and maintenance activity could be needed while the unit is in an intermediate, longterm or extended shutdown. The approach to be followed is dependent on the type of layup in use.

Access for maintenance is relatively simple when employing dehumidified air for dry layup (Step 3). The atmosphere present is safe though applicable procedures for confined space entry and general safety should be followed. Corrosion protection will continue so long as the relative humidity remains low. Thus it is advantageous to minimize the time equipment is exposed to the ambient environment. The dehumidification equipment can be left in place and in operation if this will not interfere with planned inspection and maintenance activities.

Care must be taken when the system is laid up dry with nitrogen (Step 4). The nitrogen atmosphere must be thoroughly purged with air to provide an environment suitable for entry of personnel. Since nitrogen gas does not support human life, it is extremely important that nitrogen be completely displaced by air. The atmosphere within the equipment requiring maintenance should be tested with suitable test equipment to ensure the equipment is safe for personnel entry. All other relevant plant safety precautions that apply should be followed. Further discussion is included in Section 3.3.3.

Whenever a component laid up wet (Step 5) requires inspection and maintenance, other system components should be maintained in the wet layup condition. Nitrogen feed should be secured and the component drained under atmospheric pressure. Entry for inspection and maintenance, in accordance with relevant plant procedures is then possible.

The layup condition should be reestablished as soon as possible after work is complete unless the unit will be returned to service.

3.3 Layup Protection Considerations Using Nitrogen

Shutdown periods should be viewed as a continuation of the good practices used during normal operation. The shutdown period is a prelude to the layup of the unit. Layup procedures are determined by the guiding principles for equipment protection (Section 2.3) and the duration of the shutdown (Section 2.4). Nitrogen blanketing serves an essential purpose in preventing oxygen ingress during layup.

Nitrogen blanketing is an especially significant topic, since it plays an important role in the control of corrosion in combined cycle power plants. Nitrogen may be used either to cap components that are to be maintained wet or for dry protection when applied to purge and blanket systems as they drain to prevent the entry of ambient air. In order to produce an effective nitrogen cap or blanket for oxygen exclusion from combined cycle generating unit components, both the appropriate nitrogen supply/delivery system and the appropriate application procedures are required. The final key to success is to follow the established procedures implicitly at the time the application is needed.

3.3.1 Nitrogen System Design and Operation

Combined cycle plant designers are frequently asked to include nitrogen systems as part of the plant design and the HRSG manufacturers generally include suitable points of connection for nitrogen capping or purging of their equipment. Important system design characteristics are generally common to all steam-water cycles and may be summarized as follows.

- Multiple connection points must be available to allow capping of any components or HRSG circuit to be maintained wet.
- Nitrogen system flow rates and capacity should be satisfactory for intended use.

- For nitrogen purging (draining under nitrogen) procedures, the flow rate should be sufficient to match drain rates while maintaining positive pressure so as to continually exclude air ingress.
- System capacity should be sufficient to meet anticipated requirements for use, meaning there should be enough capacity to minimize the risk of consuming all nitrogen consistent with intended operating procedures and monitoring practices. This should be considered carefully in units expected to operate in the peaking mode.
- The system must be designed in accordance with all applicable codes and standards.

Where nitrogen is to be introduced to high pressure vessels and components, double isolation valves with check valves are typically utilized. Some users choose to also provide quick-disconnect connections between the nitrogen source and the component isolation valves. This is to avoid inadvertent introduction of nitrogen to equipment when it is not desired. Such an arrangement enhances personnel safety and takes virtually no longer to activate and secure than a hard piped system.[7]

Nitrogen source and purity are important design factors deserving of careful consideration. As the purpose of applying nitrogen is to exclude the ingress of oxygen from ambient air (second guiding principle) the purity is very important. Whether purchased from a supplier or produced on site, nitrogen will contain low levels of oxygen. With effective use of high purity nitrogen, the probability of downtime corrosion is essentially eliminated. Purity levels of at least 99.5% are considered suitable for plant use.[6] Higher purity nitrogen (99.9% and greater) is possible and desirable as this will serve to minimize corrosion during shutdown.

There are three primary methods of obtaining nitrogen. Each has unique advantages and disadvantages. Equipment required with each supply option can be purchased or leased, depending upon which best suits the needs of plant personnel.

High pressure compressed gas storage is perhaps the most costly method; for this reason it is probably not desirable if frequent usage is expected. These systems are simple to operate and require relatively low inspection and maintenance.

Cryogenic liquid nitrogen storage systems are less expensive than compressed gas storage, require less frequent replacement than compressed gas storage vessels and can provide a high purity gas. The systems are simple and reliable to operate. The major drawback to the cryogenic storage system is if the system is used infrequently. Some nitrogen is continually lost each day due to pressure relief resulting from vaporization of liquid nitrogen due to accumulation of heat from the surrounding environment.

On-site production with membrane separation equipment is the third method of obtaining nitrogen for equipment protection. Although potentially least expensive, the purity of gas resulting from on-site generation is dependent on design and operating conditions. With on-site nitrogen generation systems, the rate of gas production affects the resulting purity: the faster the production, the lower the purity. In order to achieve an effective blanket by this method, component drain times might need to be very long if the system is not specified and designed to meet the expected operating conditions. These systems are more complicated and require more

operator and maintenance attention than the other options. On-site nitrogen production equipment can be either purchased or leased. If purchased, a contract for inspection and/or maintenance is necessary if this expertise is not located within the organization.

3.3.2 Application of Nitrogen

In order to provide the desired protection, nitrogen blanketing system must not only be well designed; they also must be properly operated. Procedural errors during application of nitrogen can allow corrosion to develop. Comprehensive operating procedures should be developed for the nitrogen system to cover all situations. For example, the application of a nitrogen cap to various pressurized HRSG circuits and possibly other components should consider the fact that gas must be applied before the pressure has decayed to atmospheric. Use of nitrogen to purge any components under vacuum requires a higher priority and should be done earlier in the shutdown. Thus the needs of the unit during each shutdown must be considered in the context of the protection strategy to be implemented and associated needs for nitrogen. Key actions needed here include:

- Select which parts of the system will be protected with nitrogen and how nitrogen will be applied (for wet or dry protection).
- Establish a hook-up and valve list which will accommodate this.
- Select an order in which systems will be placed in the layup condition.
- Construct a short sequential procedure that follows this order.
- Delineate the system conditions that should exist for starting to apply nitrogen to each part of the system.
- Train personnel on the procedure and included equipment.

Application of nitrogen to areas of use should start consistent with the unit shutdown procedures and anticipated outage activities. When required, application of nitrogen to steam touched components should begin with the HRSG circuits while the metal temperatures are still above the saturation temperature of the steam. Once purging is complete, isolate the circuit and maintain a slight positive nitrogen pressure on superheaters or slight flow of nitrogen through reheater circuits that are not isolatable. This is followed by purging of the main steam piping and the steam turbine, followed by the condenser shell as shutdown proceeds. As a consequence of shaft seal losses, the turbine will continually lose nitrogen to the atmosphere. Thus a slight flow of gas sufficient to maintain a slight positive pressure is necessary when using nitrogen to protect the system. Otherwise, the system could be subject to ingress of air containing oxygen and moisture. On the other hand, over pressurization can interfere with the performance of the rupture disks.

3.3.3 Plant Maintenance

Signs should be posted at all potential points of entry into confined spaces indicating that a nitrogen atmosphere might be or is present and that equipment entry is prohibited until appropriate oxygen recovery procedures have been performed on such component. If confined

space entry becomes necessary once the blanket is in place, filling the desired system with water and then draining under air usually will effectively render the component safe to enter. However it is always prudent to follow all plant safety procedures and monitor the atmosphere prior to entry even after draining under air.

A pure nitrogen atmosphere is very dangerous and potentially lethal as oxygen is necessary to sustain human life. In an oxygen-deficient atmosphere, unconsciousness is almost instantaneous, with death ensuing within minutes. Some organizations have elected to ban the use of nitrogen purging due to safety concerns. Therefore, when nitrogen is in use it must be emphasized that extreme caution is exercised in making equipment inspections if such equipment can be or has been blanketed with nitrogen. By planning when inspections are to be accomplished and by testing the atmosphere before and during the inspections, such operations can be completed safely. Development of appropriate procedures coupled with strict adherence to these procedures for entry into potentially blanketed confined spaces will result in a safe nitrogen blanketing operation.

Whenever inspection and maintenance work has to be accomplished from within the nitrogen blanketed confined space, then caution, as described above, must be practiced. If the work is to be done on the blanketed equipment from the surrounding environment, the work can proceed as normal. With the low pressure used for the blanket, nitrogen losses from any openings in the equipment to non-confined spaces will be insufficient to alter the oxygen concentration in the immediate area. If welding needs to be accomplished, the blanket pressure can be removed temporarily to make the initial welds, and then reapplied with very little loss of integrity of the blanket and corrosion protection, even in that local area. If work needs to be done from the combustion gas side of the HRSG, confined space procedures should be followed. Cracking open of the fan dampers will allow sufficient air flow as needed to correct and prevent any oxygen dilution even close to tube leak locations. Appropriate planning and procedures can allow for work to be accomplished on the blanketed equipment in many cases.

3.4 Considerations for Dry Layup Protection with Warm, Dehumidified Air

It has long been known that corrosion of metals is dependent on the environment in general. Investigations of atmospheric corrosion clearly demonstrated that corrosion of steel surfaces increases with increasing humidity level and essentially ceases under low humidity conditions. Justification for the use of dehumidified air to protect ferrous surfaces from corrosion is depicted in Figure 3-2, which is a plot of corrosion rate vs. relative humidity of air. This plot is based on early 20th century research but subsequent investigations have provided generally similar trends.

This figure illustrates that corrosion of steels can be largely mitigated by maintaining air in contact with corrosion prone surfaces at a relative humidity of 60% or less. It is normally suggested that a relative humidity of 40% or less be maintained. To provide a safety margin, systems are normally designed and operated to maintain relative humidity at no more than 30-35%. The design should include appropriate sensors to monitor humidity at appropriate locations; readings can be used for manual or automatic control of the system.

The use of clean, dehumidified air to purge fossil plant equipment during idle periods is routinely practiced worldwide. The mechanism of dehumidified air introduction, in combination with effective draining and dying of steam and water touched surfaces, is elimination of residual water and moisture as required by the second guiding principle for fossil equipment protection. At higher humidity levels, any retained water can absorb oxygen; as this water is stagnant, pitting corrosion will develop. Dehumidified air rapidly evaporates any residual water left after draining. Also, condensation of moisture can occur on surfaces if the humidity is not sufficiently low; this surface moisture can dissolve oxygen, which also allows pitting corrosion on the metal surfaces.

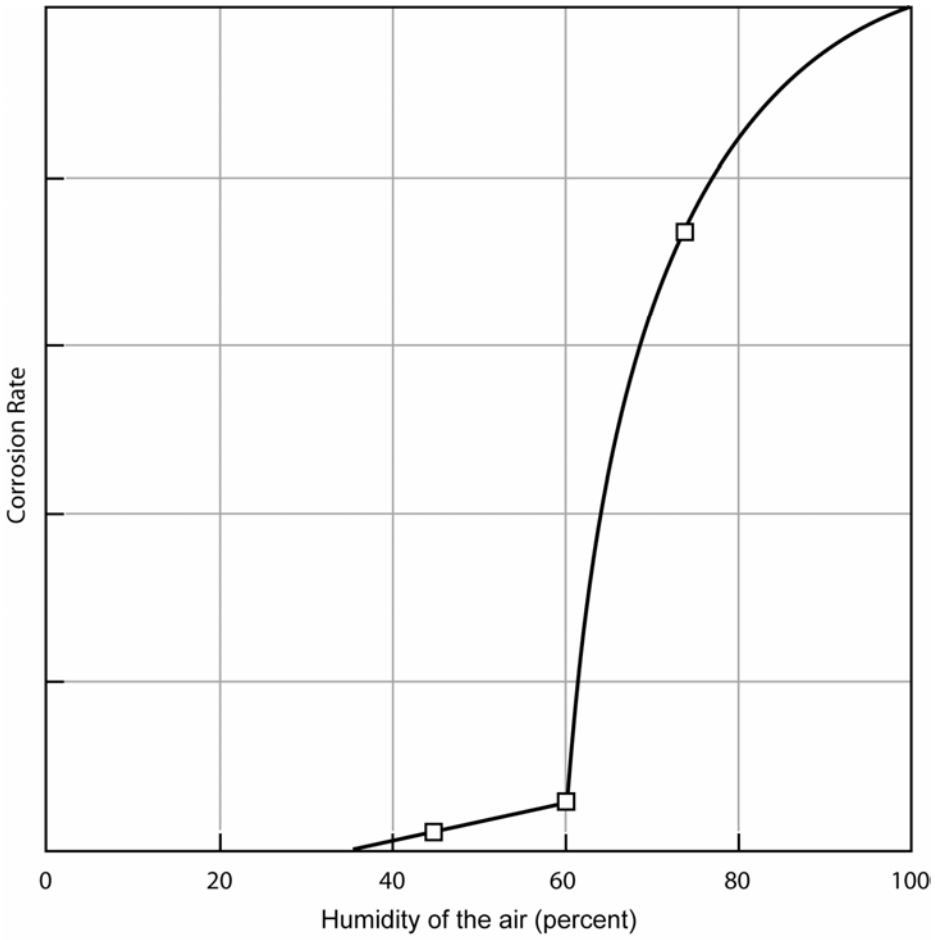


Figure 3-2
Corrosion Rate of Steel Relative to Humidity of Air

Today, dehumidified air is widely used by industry for a variety of protection and preservation purposes above and beyond corrosion control.[8] Equipment is available to provide the environment needed to meet a variety of objectives.

3.4.1 Provision of Dehumidified Air

In an earlier EPRI report,[9] it was noted that in cases where the climate at the plant site is arid it may not be necessary to produce dehumidified air. If the ambient air at the plant site is expected to be consistently dry (with a relative humidity of less than 40%) during the shutdown period, the ambient air could simply be circulated through the various systems to be protected at a nominal cost. Of course such an approach is not possible at most sites and could be risky if the actual humidity levels are higher than anticipated. However, the vast majority of plants need a suitable dehumidification system to ensure that the air is sufficiently dry at all times. Historically, the primary application of dehumidified air in power plants has been for extended protection of equipment and plant mothballing applications.[10]

A schematic drawing of the desiccant dehumidifier design commonly used for dry layup of fossil plant equipment is shown in Figure 3-3.[5,9] The dehumidifier consists of a wheel of ceramic material that has been corrugated, so air can pass lengthwise down the fluted corrugations. A desiccant is impregnated into the structure. Type 1 silica gel is the desiccant normally applied in systems for power plants. Moisture is attracted from the air onto the desiccant as the air passes through the wheel. Alternative dryer design arrangements such as multiple vertical bed systems have been offered and still may be in use at some power plants but the rotary desiccant wheel is most widely used and currently available from equipment suppliers.[11]

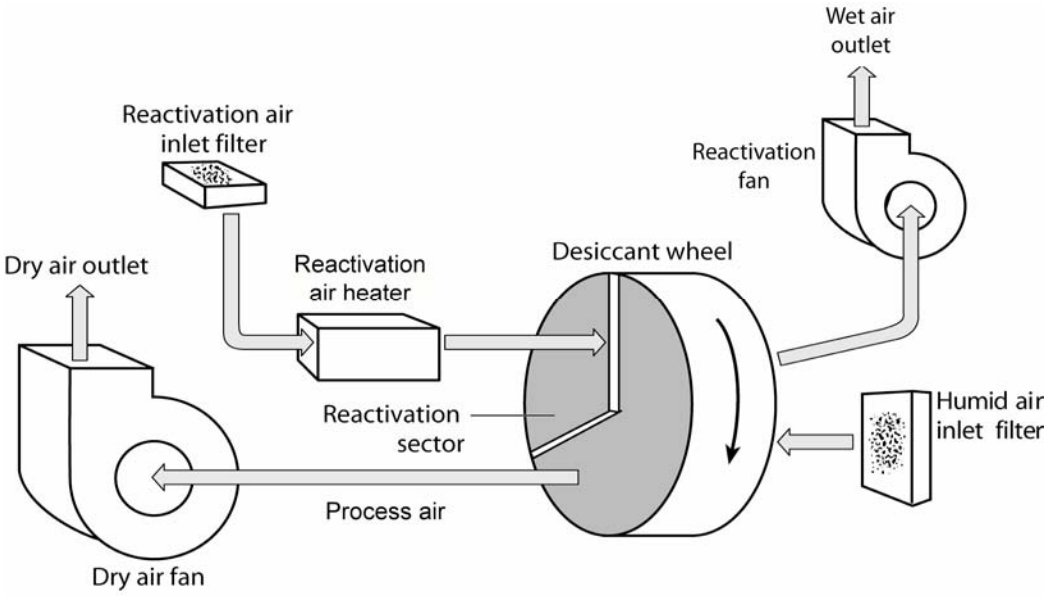


Figure 3-3
Rotary Desiccant Dehumidifier[5,9]

The wheel rotates slowly between two air streams (about one revolution every 10 minutes). The first air stream, called the process air, is the ambient air dried by the desiccant for introduction to the component or system to be protected. The air is also warmed as a consequence of dehumidification; the temperature of the process air is dependent on the temperature of the inlet air and the amount of moisture removed. The second air stream, known as reactivation air is heated and runs through the wheel in the opposite direction of the process air. Reactivation air

transfers heat to the wheel, heating the desiccant to remove and carry away its moisture so the desiccant can be reused to collect more moisture from the process air.

Other dehumidifier components include two fans, one each to pull the process and reactivation air streams through the wheel, a drive motor to turn the wheel, and a heater to warm the reactivation air stream so it can dry the desiccant. An electrical control panel coordinates the operation of the fans, drive motor, and heater.

As shown in Figure 3-3, the humid inlet air and reactivation air must both be filtered to protect the desiccant from blinding by airborne solids; however, filtration of the dehumidified process air is not practiced in most applications as entry of desiccant to the system is rare. Gross losses of desiccant, resulting from physical damage of equipment are possible but unlikely and losses due to normal attrition of the desiccant media associated with thermal cycling during operation are very minor. If desired, a system could be supplied with an outlet filter to provide further assurance that the media will not be introduced to the steam turbine or other components. High efficiency filters are available and sometimes included in systems where clean conditions are desired.[11]

While automatic controls are available, most systems are manually controlled. The rotation speed of the wheel is fixed; thus it is important to consider the allowable time for reduction of the relative humidity to the desired level and drying out of any accumulations of water that may occur during the shutdown of the unit. Operating economy during extended shutdown periods is optimized by recirculation of dry air and intermittent (on-off) operation once the humidity level has been reduced to that required for equipment protection. While losses of dry air due to leaks are undesirable, they are unlikely to result in localized corrosion if the system provides sufficient humidity monitoring capability. [11]

3.4.2 Protection in Combined Cycle Plants Using Dehumidified Air

Care must be taken in system design. While some organizations develop their own specifications, many work with the design engineers of the equipment suppliers to assess the specific needs of individual applications. For power generation applications, the allowable relative humidity is the primary design criterion. Key aspects to consider include: [11]

- Areas of the cycle to be protected.
- Optimal point or points of access for air introduction and removal.
- System capacity required (note criteria for frequency of system air changes listed earlier).
- Performance requirements: for power station applications, reduction of relative humidity in air exiting the system to 30% will provide reasonable flexibility and satisfactory protection.
- Placement of humidity sensors to monitor overall performance and ensure that any areas of possible water accumulation are quickly dried out.

As indicated earlier, it is very important that full consideration be given to system draining procedures so as to ensure insuring that there are no substantial pools or areas of free water;

otherwise oxygen pitting is a possibility at these locations until they are dry. Admission of warm dehumidified air should begin as soon as practical and while surfaces are hot enough to quickly evaporate surface moisture. Very rapid drying of steam turbine surfaces without moisture accumulation is possible if the air is applied while the metal is still hot.[11]

Effective use of humidity sensors and, to the extent possible, recirculation of dry air exiting the protected cycle components serves to quickly eliminate collection of water. Recirculation of dry air also reduces system operating costs.

The power system components to be protected must be kept as air tight as possible. The dry air circulation systems are then sized to provide adequate refreshment of dehumidified air to the component to be protected. Typical rule of thumb values for sizing are as follows[10]:

- Ten air changes per hour for all water/steam-side components, including steam turbines, HRSG circuits, feedwater system components and condensers.
- One air change per hour for flue gas-side components.
- Five to ten air changes per hour for gas turbine components and generating equipment.

If the installation does not allow the systems to be air-tight, larger values are used. If the systems are exceptionally tight, smaller values can be used, or only a portion of the circulating air can be processed through the dehumidifier. In all cases, the objective is to quickly reduce the relative humidity of the dry air to 30% or less and maintain it at these levels until the unit is to return to service.

3.4.3 Applications of Protection with Dehumidified Air

Depending on circumstances, the following possible applications of dehumidified air protection of water and steam touched surfaces are most likely at combined cycle plants:

- Protection of Steam Turbines and Other Steam Touched Surfaces
- Protection of the Entire Steam-Water Cycle

3.4.3.1 Protection of Steam Turbines and Other Steam Touched Surfaces

The need to protect the steam turbine alone is a simple application that may be needed at times when other areas of the cycle are undergoing extensive maintenance, repair or refurbishment activities that will require long outages. In such cases the turbine may need to be isolated from the steam supply piping and/or the condenser.

An example of dry layup of a steam turbine in a fossil plant is shown in Figure 3-4.[12] It is necessary to preclude any steam ingress into the laid up turbine by installing additional vents and drains (with an 8 inch (200 mm) siphon). The turbine has to be equipped with additional connection points for dry air or venting. In this case[12], two air changes per hour were sufficient for the steam turbine and condenser. In another example of dry layup of another turbine, Figure

3-5 shows the values of temperature and air humidity when using two air dehumidifiers (1 with 1.1 kW and 1 with 5.4 kW).

A more common application would involve the use of dry air to protect the turbine and other steam touched components. Protection under such a configuration could be useful for intermediate as well as longterm and extended outages. The emphasis here would be on inclusion of those steam touched components connected to the turbine that usually cannot be isolated easily and thus also may not be easily or effectively purged with nitrogen. Examples include the steam piping to the turbine, the reheater circuit (where part of the design) and the condenser steam space. Care is needed to select the optimal points of dry air ingress and egress so as to ensure that the system can be activated and secured easily as needed.

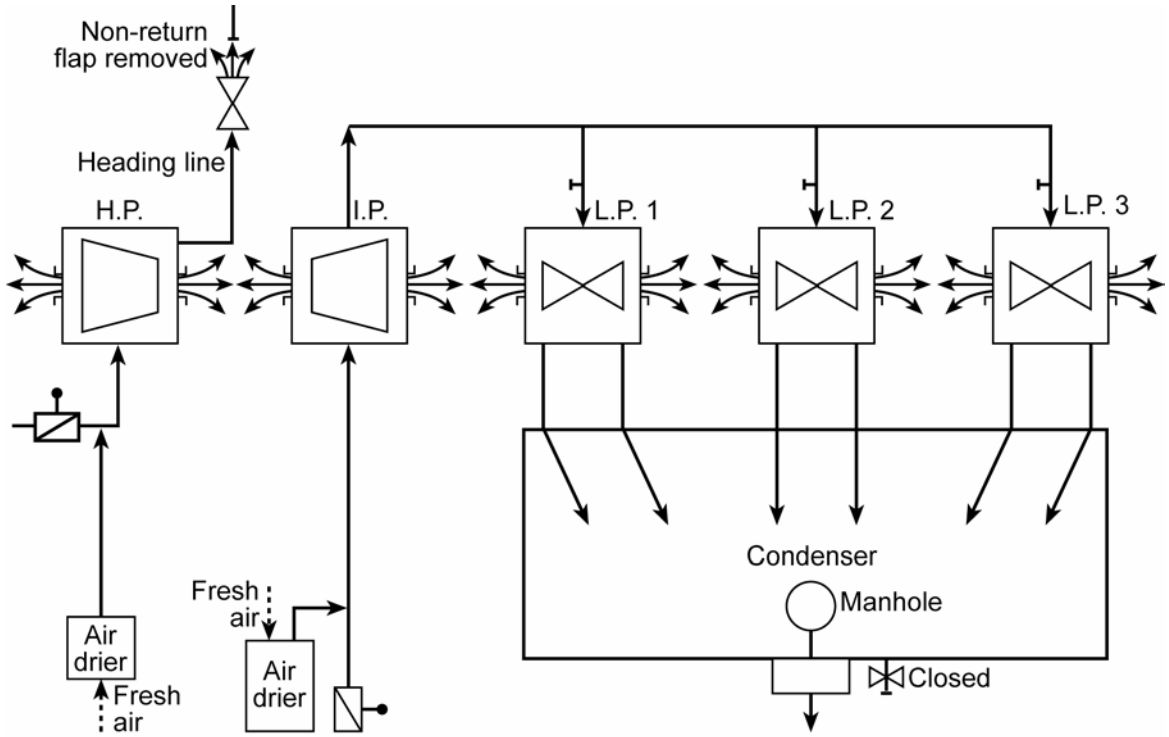


Figure 3-4
Dry Layup of 107 MW Turbine Showing Measured Values of Temperature and Air Humidity

With some designs it may be possible to keep the HRSG water touched circuits and the feedwater system laid up wet with a nitrogen blanket and the steam turbine and selected steam touched components laid up dry with warm dehumidified air. When considering any protection approach it is necessary to keep the guiding principles in mind since areas protected by dry air must avoid moisture (third principle) and areas protected wet must not be exposed to air and oxygen (second principle). In such cases the hotwell should be drained with a nitrogen purge and isolated. Superheater circuits, which should be reliably isolatable from the main steam line to the turbine, could be drained (or laid up wet) and pressurized with nitrogen. Similarly, external deaerators and storage tanks (where provided) could be laid up wet with a nitrogen cap.

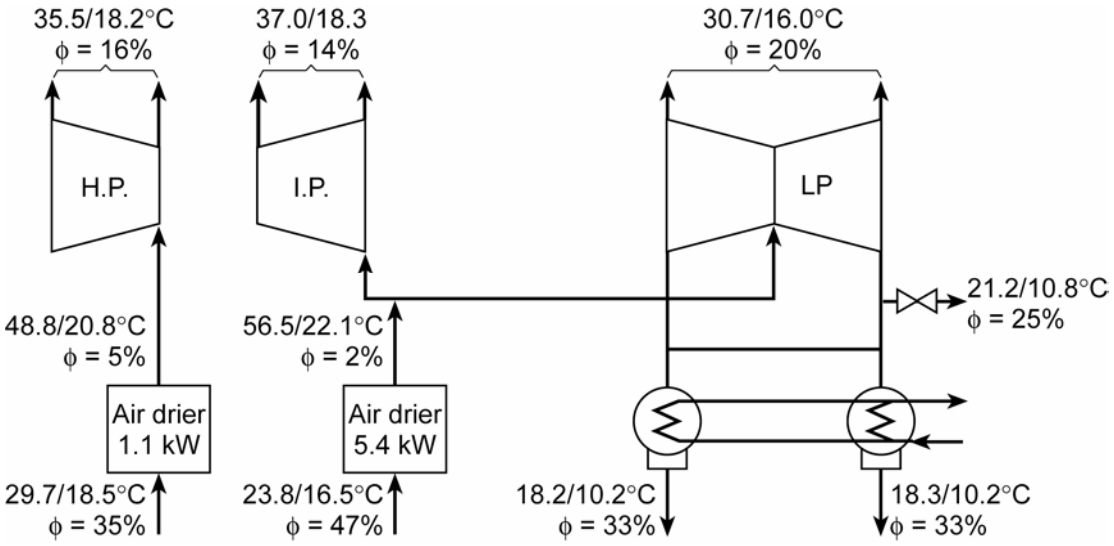


Figure 3-5
Turbine: Dry Layup Using Dehumidified Air

3.4.3.2 Protection of the Entire Steam-Water Cycle

More widespread protection is possible but requires more comprehensive analysis of the system to be protected so as to size the dry air system equipment properly. Attention must also be paid to the procedures used to shut down the unit so as to maximize removal of water when draining. Draining equipment when hot is necessary to maximize flashing of surface moisture. Experience at a conventional plant[13] has shown that moving air through equipment that is still hot can enhance the flashing and drying process; similar techniques could perhaps be developed and applied to combined cycle systems. Special care should be taken in draining of line connections that could still retain water after the major components have been drained. It is also important that all areas to be protected are completely isolated from water source connections that are pressurized during the shutdown.

For complete protection of combined cycle systems the likely points of dry air introduction and removal would typically be the condenser hotwell and the discharge side of the condensate pumps. Dehumidified air introduced to the condenser hotwell would pass through the steam turbine, reheater circuits and associated piping would be able to enter the superheaters and water touched circuits of the HRSG providing the turbine stop valves remain open. From there the dry air would pass through the feedwater system components and back to the condenser hotwell.

The system and operating procedures utilized to supply dry air for protection of the entire cycle must be customized to adapt to various heat cycle configurations. Many systems consist of two or more multistage HRSGs providing steam to a single steam turbine. The system may also include auxiliary steam connections. In complex systems, it is necessary to carefully consider all operating contingencies and design the system operating procedures accordingly.

To illustrate the thought process needed to apply warm dry air, a schematic drawing for combined cycle unit composed of a single HRSG with three drum type evaporator circuits

supplying steam to a turbine is considered as shown in Figure 3-6. One possible dry air application flow path for the system as shown in the figure can be described as follows. Dry air is discharged from the dehumidifier via a fan into the condenser and then flows through the low pressure turbine continuing through the intermediate pressure turbine section to the reheater, the high pressure turbine and the HRSG evaporator and economizer. Backward flow of warm dry air (relative to flow of water and steam in service) continues through the preheater circuit (internal to the HRSG in the figure) and the feedwater system. Dry air flows through the feedwater system, which includes an external plate type heat exchanger (bypassed) and is returned to the dehumidifier to remove moisture from the air.

Other areas of the system not all shown in the figure also can and should be protected with dehumidified air. Dry air will also pass from the hotwell through the condensate pump inlet piping and can be returned to the dehumidifier via the discharge check valves. Attemperation lines and any extraction lines are left open so dry air can pass through them.

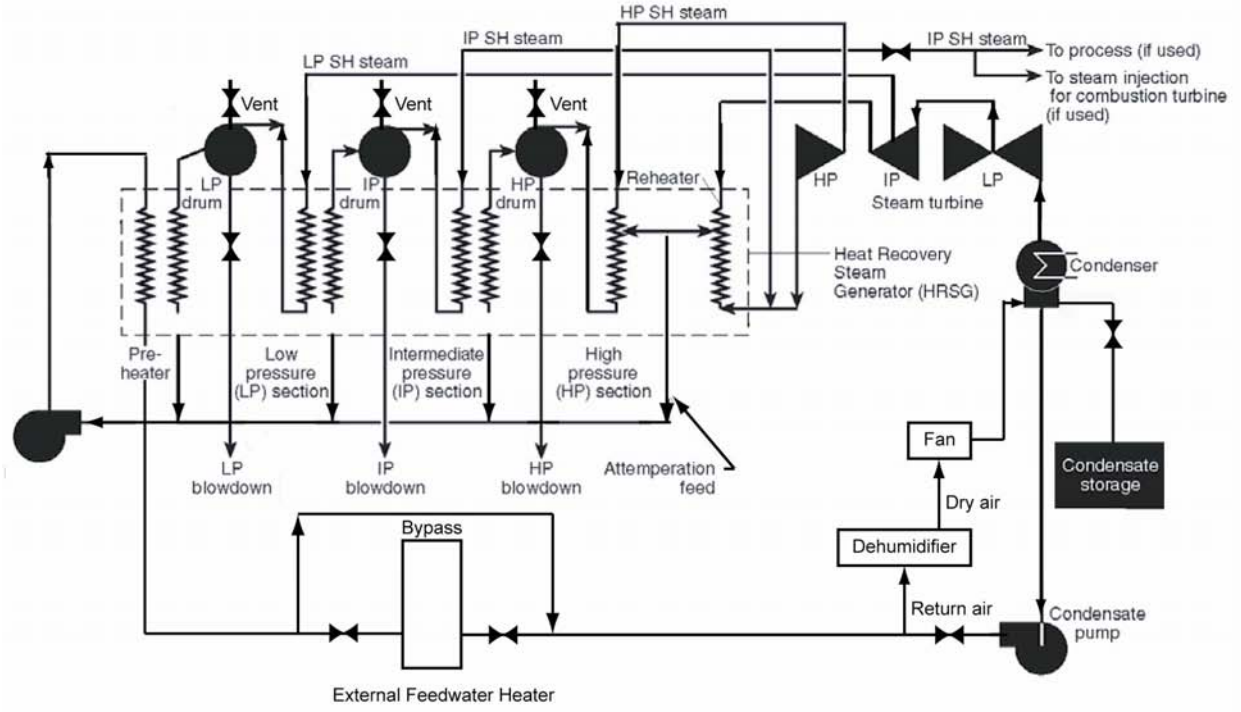


Figure 3-6
Protection of the Entire Steam-Water Cycle with Dehumidified Air

The preferred configuration is dependent on unit-specific isolation capabilities and ease of access to suitable dry air ingress and egress points. The ability of commercially available systems to effectively dry and circulate air must also be part of the assessment. Fan requirements and capabilities must be evaluated carefully in complex systems. In all applications, a system capable of reducing relative humidity of the air throughout the area being protected is the main performance criterion.

In all applications, air moisture levels should be checked at the main air egress point. Humidity sensor readings should be readily available to the operator. The humidity data should be used to control system operation for economical operation. For example, it is possible to turn the desiccant reactivation heater and blower equipment off when the relative humidity of returning air decreases to a predetermined level, say 15-20% and turn them on when humidity increases, say to >25%. Control can be either manual or automatic as desired. The extent of cycling required is dependent on tightness of the system, extent of dry air recycling, and ambient air humidity levels.

3.5 Comparison of Wet and Dry Layup Methods

An overall comparison of the operational advantages and disadvantages of wet and dry layup methods indicated in the Figure 3-1 roadmap of Section 3.2 and discussed further in Sections 3.3 and 3.4 is given in Tables 3-1 to 3-3. The possible disadvantages have been successfully overcome in other plants but should carefully be considered when developing procedures for application to individual units. When considering and selecting layup procedures for a specific HRSG and its related equipment, responsible personnel should always be cognizant of the guiding principles for equipment protection as is emphasized throughout these guidelines. The optimal operational chemistry treatment for the feedwater and each evaporator circuit should also be kept in mind.

As discussed at length previously, EPRI research clearly indicates the importance of avoiding loss of passivation of steam turbine surfaces during shutdown periods. For protection of the turbine from loss of passivation, which can ultimately lead to damage by corrosion fatigue and stress corrosion cracking, use of warm, dehumidified air is considered superior to other methods, including nitrogen blanketing. To protect the turbine with nitrogen, a relatively large system is required due to the seal losses; nitrogen systems sized to cap the wet circuits of the HRSG and the feedwater system could be incapable of meeting the turbine protection requirement. Most of the major steam turbine manufacturers now indicate maximum allowable time intervals after which the turbine requires protection; these intervals range from about 2-7 days. Use of dehumidified air is generally specified as the preferred method of protection.

Table 3-1
Shutdown and Layup Advantages and Disadvantages: Wet Layup

Wet Layup* with Nitrogen Cap ***Typically with ammonia only; reducing agents not allowed without copper in feedwater system**	
Advantages	**Disadvantages**
1. No change in chemistry for short term shutdowns 2. Easily tested and maintained 3. Can also be used for longer shutdowns	1. Requires nitrogen cap be applied before air can enter the system 2. Need to circulate and monitor wet layup solutions regularly 3. Should not be used when freezing is possible 4. System must be drained under air if entry is required. 5. Refilling requires high purity water of low dissolved oxygen content 6. Ammonia must not be added if copper or copper alloys are present in the system 7. Tight isolation is needed to avoid leaks 8. If chemicals are added for longer shutdowns, it may be necessary to drain, rinse and refill prior to startup; also possible waste disposal concern

Table 3-2
Shutdown and Layup Advantages and Disadvantages: Nitrogen Blanketing

Nitrogen Blanketing	
Advantages	**Disadvantages**
1. System need not be completely dry 2. Protection independent of climatic conditions 3. May also be used to cap normal operating fluid during short outages	1. Does not support life; use prohibited by some organizations; requires air purge prior to entry 2. Should be applied before air can enter components to be protected 3. Cost of nitrogen and distribution and control equipment 4. Nitrogen pressure cannot be maintained if system valves leak 5. Reheater normally cannot be isolated

Table 3-3
Shutdown and Layup Advantages and Disadvantages: Dehumidified Air

Dry Layup with Dehumidified Air	
Advantages	**Disadvantages**
1. Utilizes ambient air 2. No risk to personnel 3. Residual heat in metal utilized for drying 4. Whole unit or individual components may be protected 5. Independent of ambient temperature if air dry enough 6. Maintenance on plant performed without problems 7. Easy monitoring 8. Tolerant of small system leaks	1. Drying equipment and blowers required and consume power when used 2. Climatic conditions may influence storage conditions; minimized in tight systems 3. Drying of surfaces should be maximized while draining; even draining hot and under pressure does not ensure immediate water removal though any residual water or moisture eventually will be removed by the dry air 4. Time is required to activate, monitor and deactivate the system

The near exclusive use of dehumidified air for protection of fossil cycle components including those of combined cycles continues to be on an as required basis for extended or mothballing protection, as may be needed for various reasons. Traditionally, such applications have involved leasing of the equipment involved. Field experience has shown that it is generally possible to bring the dehumidification equipment to the plant and conveniently position it and connect it to the cycle at one or more locations as may be needed. Thus it should be possible to do so with permanent systems where desired.

Further, the trend towards designing of combined cycle units for seasonal peaking service has reportedly resulted in a few cases where the anticipated need for more frequent use of dry air, such as for longterm and extended protection has been recognized and the requisite equipment included in the design as a permanent system. Thus these newer units with permanent dehumidification systems will be better positioned to provide protection of the turbine even during intermediate term outages as is indicated to be desirable based on EPRI research and generally recommended by the manufacturers.

For those plants not so equipped and subject to frequent intermediate term outages, consideration should be given to provision of an on-site dehumidification system capable of protecting the steam turbine. In most cases, it should be possible to engineer and size the system to protect the steam turbine, any reheaters and associated steam touched piping. Provision of equipment needed for dehumidified air protection of the entire cycle could still be leased on an as needed basis if desired.

Layup method assessment should also consider the following unit-specific factors:[14]

- The nature and expected duration of the shutdown.
- The possibility the shutdown duration may be required for operation on short notice.
- Facilities available for proper disposal of layup solutions.
- The possibility of freezing conditions during shutdowns.
- The practicality of establishing and maintaining all the required conditions of a given procedure with available resources.
- Local atmospheric conditions, e.g., salt air environment.
- The availability of sufficient high purity condensate, deaerated demineralized water, nitrogen or dehumidified air during the unit outage.

Finally, it should be understood that to take no action with respect to protection of the steam water cycle during shutdowns is an unacceptable choice as it will lead to off-line corrosion, breakdown of protective oxide films and transport of iron oxides to the HRSG during startups. It thus invites premature failures of HRSG tubing due to pitting attack. It also restricts the advantages to be derived from proper selection and optimization of the operating cycle chemistry.

3.6 Monitoring During Storage

An essential part of layup is to monitor the integrity of all systems for proper chemistry, loss of pressure, loss of fluid or gases, and an adequate supply of dehumidified air or nitrogen.

Operation of manually controlled dehumidified air systems should be checked daily and the relative humidity levels reviewed. Pressure gages should be monitored on a weekly basis to verify the absence of leaks in the systems capped or blanketed with nitrogen.

All wet layup solutions should be circulated at least weekly to avoid development of stagnant conditions and ensure good mixing of these solutions. During intermediate or longterm shutdowns circulation should be followed by sampling, using sample connections which yield representative samples of the layup solutions.

Additional chemicals should be added to replenish those that have deteriorated or lost by leakage. Leaks should be detected promptly and repaired to prevent loss of chemicals and nitrogen or dehumidified air.

3.7 Environmental Considerations

The disposal of layup solutions containing high concentrations of alkaline chemicals such as ammonia, and/or high concentrations of reducing agents (only for units with AVT(R) feedwater chemistry) such as hydrazine or hydrazine substitutes, poses potential problems from an environmental standpoint. The solution to these potential problems may require modifications to

existing waste treatment facilities. The cooperation of regulatory authorities should be a part of the investigative process necessary to resolve these environmental issues.

3.8 References

1. *Delivering High Reliability Heat Recovery Steam Generators*. EPRI, Palo Alto, CA: 2003. 1004240.
2. *Heat Recovery Steam Generator Tube Failure Manual*. EPRI, Palo Alto, CA: 2002. 1004503.
3. *Guidelines for Controlling Flow-Accelerated Corrosion in Fossil and Combined Cycle Plants*. EPRI, Palo Alto, CA: 2005. 1008082.
4. *Survey Results. Proceedings: Boiler Tube and HRSG Tube Failure and Inspection International Conference*: November 2-4, 2004, San Diego, California. EPRI, Palo Alto, CA: 2004. (Publication pending.)
5. *Cycle Chemistry Guidelines for Combined Cycle/Heat Recovery Steam Generators (HRSGs)*. EPRI, Palo Alto, CA: 2006. 1010438.
6. *Cycle Chemistry Guidelines for Fossil Plants: Oxygenated Treatment*. EPRI, Palo Alto, CA: 2005. 1004925.
7. R. D. Wine, "Effective Nitrogen Blanketing of Power Generating Equipment for Oxygen Exclusion and Corrosion Control", Presented at the 21st Annual Electric Utility Chemistry Workshop, University of Illinois, May 2001.
8. L. G. Harriman III, ed., *The Dehumidification Handbook*, Second Edition, Munters Corporation, Amesbury, MA. 2002.
9. *Sourcebook for Plant Layup and Equipment Preservation (Revision 1)*. EPRI, Palo Alto, CA:1992. NP- 5106.
10. D. Kosar, "Power Plant Preservation Using Desiccant Dehumidifiers", *Proceedings: Fossil Plant Layup and Reactivation Conference*, EPRI, Palo Alto, CA: 1992. TR-101250.
11. J. Siemasko, Munters Corporation, personal communications with K. Shields, May and July 2005.
12. H. Steger, "Standby Corrosion Prevention in Power Plants" (in German). *Der Maschinenschaden*, Vol. 49, No. 1, pp. 23-27, 1976.
13. M. E. Walker, "Passivation of Unit 3 State Line Station through Dehumidification", Proceedings: Fossil Plant Layup and Reactivation Conference, EPRI, Palo Alto, CA: 1992. TR-101250.
14. *The ASME Handbook on Water Technology for Thermal Power Systems, American Society of Mechanical Engineers*, New York, NY. 1989.

4
SHUTDOWN FOR VARIOUS CYCLE CHEMISTRIES

4.1 Shutdown Requirements for the Various Cycle Chemistries

Some of the design aspects of plants, which influence the establishment of shutdown procedures, are outlined in a recent EPRI publication[(1)]. They include operational aspects, such as steam drum temperature, rate of cooling and pressure decay, and how these can be minimized and used to maintain off-load conditions suitable for a fast restart.

Three guiding principles for chemical conditions given in Section 2.3 of this report, should be used to minimize off-load corrosion. They may be summarized as follows:

i) Maintain the same potential (oxidizing/reducing conditions) for shutdown, layup and startup as during normal operation, i.e., when using AVT(O) or OT, do not add a reducing agent during shutdown. (Only when copper alloys are present in the feedwater system is it appropriate to use AVT(R); during shutdown it is necessary to maintain reducing conditions and keep air out.)

ii) Prevent the water from becoming oxygenated by preventing air ingress, by using nitrogen or steam blanketing and avoid stagnant conditions.

iii) Keep water and moisture out of steam touched components by maintaining dry conditions during shutdown by rapidly draining during shutdown and, if necessary, adding warm dehumidified air to protect the steam turbine and reheaters.

An HRSG unit may consist of several pressure stages. These may all be operated using the same method of chemical conditioning, e.g., AVT or OT. However, some may operate with a combination of AVT or OT, and solid alkali added to the low pressure evaporator water. Others could operate with different solid alkali concentrations in the various pressure stages. The chemical conditions at shutdown and layup during short outages should be the same as expected during normal operation. However, care is needed during startup to ensure that the chemical conditions (e.g., PC or CT) in one pressure stage (e.g., LP) do not adversely affect the chemical conditions in other pressure stages or other areas of the cycle, through the feedwater or due to increased mechanical carryover.

Shutdowns may be needed for maintenance, either planned or unplanned, or for reasons of economy. Chemistry excursions during service, if severe enough, can also require shutdown to protect equipment from damage and possible failure. Such shutdowns typically require inspection, maintemance and other actions before the unit is returned to service.

Chemistry variations from normal requiring unit shutdown are generally associated with contamination of the steam-water cycle for various reasons. When the unit employs a water cooled condenser condenser cooling water leakage is a possible and often significant source of contamination. In combined cycle units the condener tube material is often titanium or, where cooling water characteristics permit, stainless steel. Use of copper alloy tubing, typically more prone to leaks over the operating life is less commonly used.

Timely detection and repair of condenser leaks during operation is critical to minimize potential damage by harmful contaminants such as chlorides and sulfates. Impurities will concentrate in drum evaporator circuits where they may cause corrosion. In once-through evaporator circuits, impurities will enter the steam touched circuits and steam turbine. Condensate polishers can help decrease the impacts of contaminant ingress on chemistry but are not commonly provided on combined cycle units. Units without polishers experiencing condenser leaks, regardless of cooling water chemistry characteristics, or subject to contamination from other sources generally should be shut down to protect the evaporators and steam path components.

Protection of equipment is of importance during all shutdowns and methods to be applied should be selected in consideration of the expected duration of the shutdown and the nature of any inspection and maintenance required. Section 3 describes the available approaches that are suitable for various situations.

As most combined cycles do not include copper in the feedwater system, oxidizing all volatile treatment, AVT(O), is suitable for the majority of units, while a few may be able to operate beneficially with oxygenated treatment (OT). Reducing agents should not be added in cycles employing these feedwater treatments and ensuing discussions of shutdown reflect this. (Only units with copper in the feedwater system should apply a reducing agent such as hydrazine to establish reducing AVT conditions.)

The various methods of chemical conditioning are considered in the following sections in the same order as they appear in the recently revised Cycle Chemistry Guidelines for Combined Cycle/Heat Recovery Steam Generators (HRSGs)[(2)].

Since, in some cases, the circuits of multi-pressure HRSGs may operate on different cycle chemistries and also may include both drum type and once-through circuits, operators should consider all of the sections which follow that are relevant to the HRSG of interest, to ensure that customized shutdown procedures developed comply with the guiding principles of Section 2.3, as well as the requirements of Sections 4.2 to 4.7 which follow.

4.2 Phosphate Continuum Treatment for Drum HRSG Circuits

As described in the HRSG Cycle Chemistry[(2)] and phosphate guidelines[(3)], phosphate continuum (PC) treatment was designed to cover a wide range of operating pressures and boiler characteristics. Two sets of control curves were developed. Low levels of phosphate may be used when there is only a need for low levels of protection from contamination in the evaporator circuit. When the potential for contamination and thus the need for corrosion protection of the evaporator circuits is greater, higher levels of phosphate may be applied; this is known as PC(H).

In high pressure evaporator circuits, it is very important to measure the carryover to verify that the treatment will not contaminate the steam. At higher evaporator pressures operating at or above 2000 psi (13.8 MPa) it is usually possible to use only PC(L). However, In some HRSG designs, it may be possible to use PC(H) in the low pressure and intermediate pressure circuits while using PC(L) in the high pressure evaporator circuits.

The pH and the phosphate concentration of each circuit treated with PC should be monitored closely when a unit trips. A sudden release of phosphate (hideout return) may indicate that the phosphate concentration used during normal operation is too high. As a rule, any phosphate hideout return causes a pH increase in the evaporator water.

During shutdown, the pH may also increase as the result of the phosphate hideout return. The pH should be maintained within the selected control range even during shutdown. If necessary, sodium hydroxide can be added to drive the pH into the acceptable range to protect the HRSG.

A road map for shutdown of HRSG evaporator circuits employing phosphate continuum (PC) chemistry is presented in Figure 4-1. Shutdown should be closely related to layup, which in turn, depends on the anticipated outage length. Based upon this road map, shutdown should proceed in the following manner.

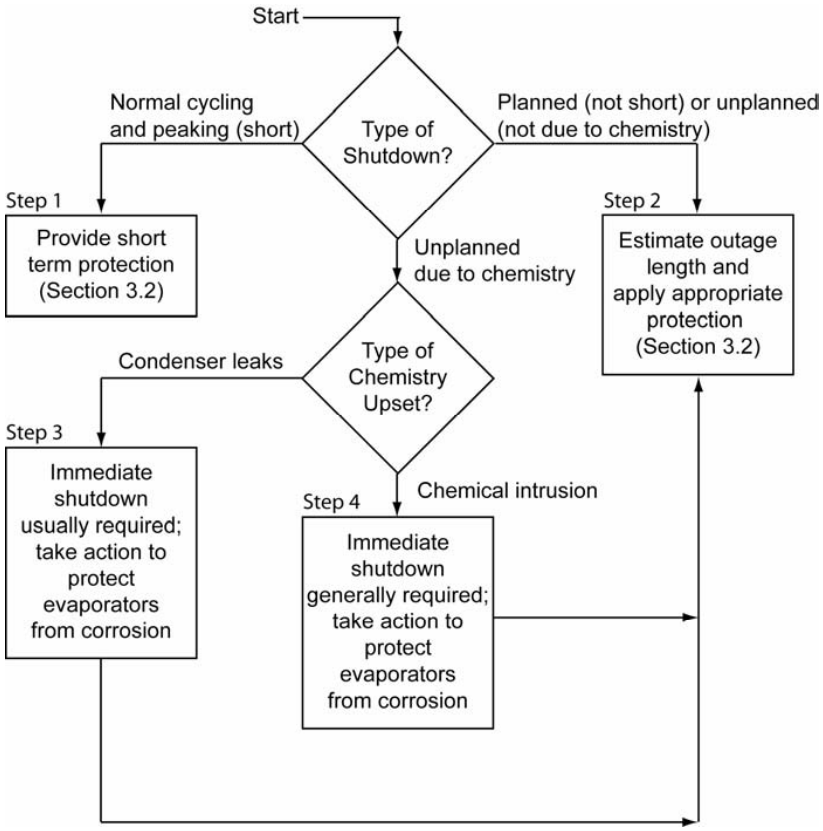


Figure 4-1
Road Map for Shutdown of Combined Cycle Units with Drum Type Evaporator HRSG Circuits Using Phosphate Continuum (PC) Chemistry

The road map for shutdown for phosphate continuum units, Figure 4-1, should be used in conjunction with Figure 3-1 in Section 3.2.

Figure 4-1 can be divided into four steps.

Step 1 – Normal Cycling or Peaking: Load Reduction or Shutdown

Normal cycling or peaking load reduction or shutdown presumes a short term shutdown and use of protection measures as described in Section 3.2 and Step 1 of the Figure 3-1 road map.

An orderly reduction of load can be performed for routine cycling operations. Also, an orderly reduction of load or unit shutdown can be performed when contamination is minimal, as determined by chemical monitoring during such transients.

During orderly load reductions, the cycle chemical limits for evaporator water should be adjusted to conform with the phosphate continuum chemistry guidelines[2, 3] in use, PC(L) or PC(H) as applicable. (Layup procedures are covered in Section 3.2 of this document.)

Particular care should be exercised to monitor unit conditions (temperatures and pressures plus condenser vacuum) during the shutdown so as to prevent air ingress; action should be taken to provide another form of protection before this occurs. Blowdown should be maintained at an appropriate level to remove contaminants from the system.

During shutdown, any indication of phosphate hideout return (increased levels of phosphate, change of pH, etc.) indicates that the evaporator has not been operating at the optimum level during normal operation. This should be corrected during normal operation by following the procedure given in the HRSG Cycle Chemistry[2] and phosphate guidelines[3] to determine the optimum level of phosphate.

Step 2 – Other Shutdowns

Duration of planned or unplanned outages will depend on system demand or the extent of the work required before returning the unit to operation. These shutdowns typically require intermediate, longterm or extended protection. The length of time required for maintenance must be estimated and, depending on this estimate, an appropriate layup should be initiated. For longer wet layups, adjustment of chemistry prior to shutdown may be desirable. See Section 3.2 discussion and the Figure 3-1 road map.

An unplanned shutdown caused by chemistry upsets (additional shutdown requirements are discussed in Steps 3 and 4) and outages due to an equipment or system failure can be treated as for a planned outage.

Step 3 – Chemical Transients: Condenser Leakage

The level of contamination in the cycle is dependent on both the amount of cooling water ingress (size and number of leaks) and, usually more importantly, the cooling water dissolved solids

concentration. Evaporator water pH control is critical and monitoring condensate cation conductivity and sodium levels will assist in estimating the magnitude of the leak. The addition of extra trisodium phosphate or 1-2 ppm of sodium hydroxide may be required, if the evaporator water pH drops. Immediate shutdown of the unit is required if the evaporator water pH falls below 8.

Chemistry monitoring is especially important when a condenser leak is suspected to be developing and the cooling water is a high solids water such seawater, brackish water or high solids cooling tower water. Without condensate polishing (as is usually the case), evaporator water pH is impossible to control in such cases and immediate shutdown is required because, with continued operation, serious damage can occur to evaporator tubes within a short period of time.

On units with condensate polishing, there is greater flexibility in dealing with leaks that do not rapidly depress the evaporator pH to levels requiring immediate shutdown; unit shutdown can generally be accomplished in a more orderly fashion.

For small condenser leaks in units using fresh, relatively low dissolved solids cooling water, it may be possible to avoid shutdown when the HRSG consists of drum evaporator circuits only; however a load reduction would be needed. Avoidance of shutdown requires: effective chemistry instrumentation to identify the leak promptly; the ability to rapidly and effectively isolate the area of the condenser experiencing leakage (divided waterbox design): and reliable identification and plugging of all leaks. It cannot be overemphasized that such action will be successful only if rapid leak detection results in immediate action to reduce load and isolate the condenser. Evaporator chemistry must be watched very closely if in-service assessment and repairs are attempted; it may be necessary to take actions such as reducing pressure, blowing down and addition of extra trisodium phosphate or sodium hydroxide to the evaporator. If evaporator chemistry cannot be controlled, the unit should be shut down promptly, and the leaks isolated and repaired.

Generally, the unit should be shut down to repair the condenser leak.

Substantial intrusion of any cooling water, such as may follow mechanical damage of several tubes within the condenser, into the HRSG will require that the unit be shut down immediately. It should then be drained, flushed and refilled with condensate quality water plus chemicals consistent with operating requirements of PC treatment.

Step 4 – Chemical Transients: Chemical Intrusion

Some of the many possible causes of chemical intrusion (in addition to condenser leakage) include:

- Makeup water system malfunction
- Chemical cleaning residue; acid, caustic, other
- Maintenance chemicals and preservatives

Minor chemical intrusions can be controlled by increasing evaporator circuit blowdown.

More serious chemical intrusions may require adjustment of evaporator water pH through addition of more trisodium phosphate or 1-2 ppm of sodium hydroxide. If these treatments are unsuccessful, the unit must be shut down if the pH falls below 8.0[(2)]. The unit then requires careful inspection to determine possible damage, and the necessity for repair and possible chemical cleaning prior to restart.

Intrusion of chemical contamination requires immediate unit shutdown, draining and flushing the unit. Inspection of critical areas of the system (evaporator circuits, superheater, turbine, etc.) should be performed to assess the effects of chemical intrusion on the system. Chemical cleaning of the affected components may be required depending upon the results of the inspection. Equipment repairs may also be required. In such case, a longterm layup will be required (see Section 3.2).

During emergency shutdowns, such as for major condenser leaks and extensive chemical contamination, immediate unit shutdown is required. Therefore, little can be done to adjust cycle chemistry during shutdown, since rapid action is required. During such occasions, the unit should be drained, flushed and inspected to assess damages, as outlined previously. Restarting the unit will be contingent upon this inspection, as will layup provisions.

4.3 All Volatile Treatment for Drum HRSG Circuits

General information on shutdown and layup protection for various planned shutdown conditions is given in Section 3. Selection of protection measures should consider the governing guiding principles of Section 3.2.

Unplanned shutdowns also occur and, by their very nature, are unpredictable. Evaporator circuits employing all volatile treatment (AVT) have no corrosion protection. Contaminated feedwater entering such circuits will generally result in corrosive and usually low pH conditions. Damage and failure of evaporator tubing will occur unless prompt action is taken. This normally requires shutdown of the unit and addition of solids based treatment chemicals (trisodium phosphate, sodium hydroxide) to the evaporator circuits.

A road map showing a scheme for shutdown of a drum type HRSG with an all-ferrous feedwater heating system operating with AVT is given in Figure 4-2. The time taken to achieve stable shutdown conditions will be plant dependent. This should be determined for each unit, used as guidance for future operations and amended in the light of operating experience.

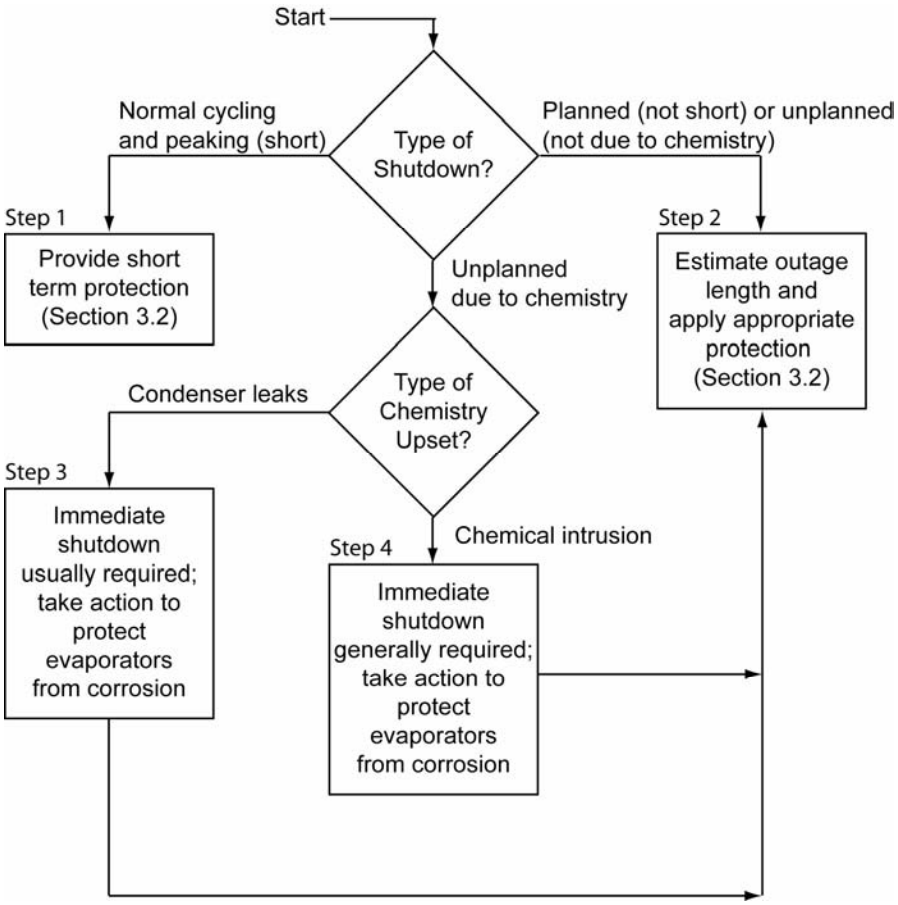


Figure 4-2
Road Map for Shutdown of Combined Cycle Units with Drum Type Evaporator HRSG Circuits using All Volatile Treatment (AVT)

The road map for shutdown of a drum-type HRSG unit operating on AVT with an all-ferrous cycle, Figure 4-2, can be divided into four steps.

The steps are essentially similar to those described for PC (Section 4.2). In drum type HRSG circuits operating on AVT, blowdown can be used for control of the evaporator water purity for control of silica and, in the absence of contamination, other impurities that enter and concentrate in the circuit.

Step 1 – Normal Cycling or Peaking: Load Reduction or Shutdown

Normal cycling or peaking load reduction or shutdown presumes a short term shutdown and use of protection measures as described in Section 3.2 and Step 1 of the Figure 3-1 road map.

An orderly reduction of load can be performed for routine cycling operations. Also, an orderly reduction of load or unit shutdown can be performed when contamination is minimal, as determined by chemical monitoring during such transients.

During orderly load reductions, the feedwater and evaporator water chemical limits should be adjusted to conform with the HRSG Cycle Chemistry[2] for drum evaporator units and the latest AVT Chemistry Guidelines.[4].

Particular care should be exercised to monitor unit conditions (temperatures and pressures plus condenser vacuum) during the shutdown so as to prevent air ingress; action should be taken to provide another form of protection before this occurs. Blowdown should be maintained at an appropriate level to remove contaminants from the system.

Step 2 – Outages

Duration of planned or unplanned outages will depend on system demand or the extent of the work required before returning the unit to operation. The length of time required for maintenance must be estimated and, depending on this estimate, an appropriate layup should be initiated. For longer wet layups, adjustment of chemistry prior to shutdown may be desirable. See Section 3.2 discussion and Figure 3-1.

An unplanned outage due to an equipment or system failure can be treated as for a planned outage.

Step 3 – Chemical Transients: Condenser Leak

The level of contamination in the cycle is dependent on both the amount of cooling water ingress (size and number of leaks) and, usually more importantly, the cooling water dissolved solids concentration. Evaporator water pH control is critical and monitoring condensate cation conductivity and sodium levels will assist in estimating the magnitude of the leak.

In drum type evaporator circuits using AVT chemistry, the pH will begin to fall almost immediately, often serving as the first indication of contamination. Immediate shutdown of the unit is required if the evaporator water pH falls below 8. Addition of trisodium phosphate or sodium hydroxide will help minimize corrosion damage.

Chemistry monitoring is especially important when a condenser leak is suspected to be developing and the cooling water is a high solids water such seawater, brackish water or high solids cooling tower water. Without condensate polishing (as is usually the case), evaporator water pH is impossible to control in such cases and immediate shutdown is required because, with continued operation, serious damage can occur to evaporator tubes within a short period of time. Even leaks of low solids cooling water will usually depress the pH and thus require immediate shutdown of the unit.

On units with condensate polishing, there is greater flexibility in dealing with small leaks that do not rapidly depress the evaporator pH to levels requiring immediate shutdown. Also, unit shutdown can generally be accomplished in a more orderly fashion.

Substantial intrusion of any cooling water, such as may follow mechanical damage within the condenser, into the HRSG will require that the unit be shut down immediately. It should then be drained, flushed and refilled with condensate quality water plus chemicals consistent with operating requirements of AVT chemistry.

Step 4 – Chemical Transients: Chemical Intrusion

Some of the many causes of chemical intrusion (in addition to condenser leakage) include:

- Makeup water system malfunction
- Chemical cleaning residue; acid, caustic, other
- Maintenance chemicals and preservatives

Minor chemical intrusions can be controlled by increasing evaporator blowdown.

More serious chemical intrusions may affect (lower) the evaporator circuit pH, necessitating adjustment of pH through the addition of trisodium phosphate or 1-2 ppm sodium hydroxide (see Sections 4.2 and 4.5). If these treatments are unsuccessful, the unit must be shut down (orderly with polishers, immediately without polishers) if the pH falls below 8[(2)]. The unit then requires careful inspection to determine possible damage, and the necessity for repair and possible chemical cleaning prior to restart.

Intrusion of chemical contamination often requires immediate unit shutdown, draining and flushing the unit. Inspection of critical areas of the system (evaporator circuits, superheater circuits, turbine, etc.) should be performed to assess the effects of the chemical intrusion. Chemical cleaning may be required, depending on the results of the inspection. Equipment repairs may be required. In such case, a longterm layup will be required (See Section 3.2).

During emergency shutdowns, such as for major sea water leaks and extensive chemical contamination, immediate unit shutdown is required. Therefore, little can be done to adjust cycle chemistry during shutdown, since rapid action is required. During such occasions, the unit should be drained, flushed and inspected to assess damage, as outlined previously. Restarting the unit will be contingent upon this inspection, as will layup provisions.

4.4 All Volatile Treatment for Once-Through HRSG Circuits

Only a limited number of HRSGs include once-through evaporator circuits; in many cases, the feedwater to this circuit is provided by a low pressure evaporator. The design includes a condensate polisher or filter in some but not all cases; this equipment, when present, may only be sized to handle full flow during startup of the unit.

Information is given in Section 3.2 (see Figure 3-1) and below for various planned shutdown conditions. Unplanned shutdowns also occur and, by their very nature, are unpredictable. Chemical contaminants entering once-through evaporator circuits will also enter the steam path; prompt shutdown is required to prevent deposition and corrosion in superheater and reheater circuits as well as steam turbines. Protection of the turbine is vitally important following such events.

A road map for shutdown of a HRSG with a once-through evaporator circuit operating with AVT(O) is given in Figure 4-3. The time taken to achieve stable shutdown conditions will be plant dependent. This should be determined for each unit, as guidance for subsequent shutdowns and amended in the light of operating experience.

The road map for shutdown of once-through HRSG units operating on AVT(O), Figure 4-3, can be divided into four steps.

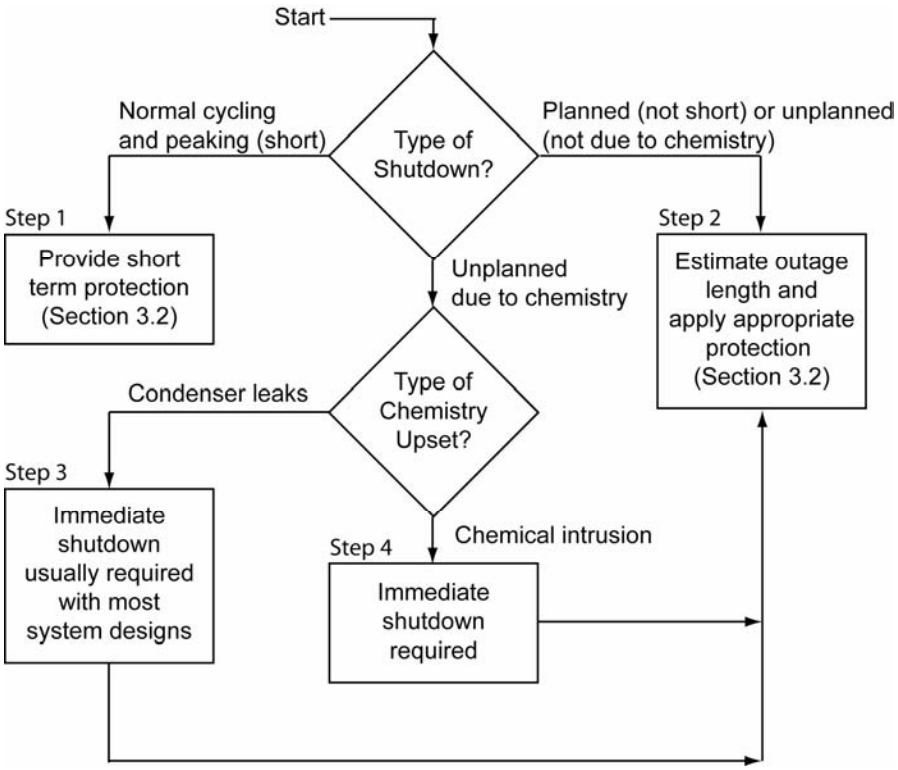


Figure 4-3
Road Map for Shutdown of Combined Cycle Units with Once-Through Evaporator HRSG Circuits using All Volatile Treatment (AVT)

The steps are essentially similar to those described in Section 4.3 for units with drum type evaporators, except that for once-through circuits, very high purity water is required for the evaporator, as well as the feedwater (and steam), and control of the evaporator water purity can not be achieved by blowdown.

Step 1 – Normal Cycling or Peaking: Load Reduction or Shutdown

Normal cycling or peaking load reduction or shutdown presumes a short term shutdown and use of protection measures as described in Section 3.2 and Step 1 of the Figure 3-1 road map.

An orderly reduction of load can be performed for routine cycling operations. Also, an orderly reduction of load or unit shutdown can be performed when contamination is minimal, as determined by chemical monitoring during such transients.

Step 2 – Shutdowns

Duration of planned or unplanned outages will depend on system demand or the extent of the work required before returning the unit to operation. The length of time required for maintenance must be estimated and, depending on this estimate, an appropriate layup should be initiated. For longer wet layups, adjustment of chemistry prior to shutdown may be desirable. See Section 3.2 discussion and Figure 3-1.

An unplanned outage due to an equipment or system failure can be treated as for a planned outage.

Step 3 – Chemical Transients: Condenser Leak

In once-through evaporator circuits, concentration of solids will not occur; some deposition is possible but steam path contamination and resultant damage is of greater concern. Thus the correct response action upon identification of condenser leakage is to shut the unit down to repair the leak.

With condensate polishing, the unit can generally be shut down in a more orderly fashion. However, most units with once-through evaporators have no or only partial flow polishing capability.

Depending on an evaluation of the cycle chemistry, shutdown should be immediate or orderly, as outlined above.

Substantial intrusion of cooling water into the HRSG will require that the unit is drained and refilled with condensate quality water meeting the HRSG Cycle Chemistry Guidelines[(2)] for once-through units operating on AVT.

Step 4 – Chemical Transients: Chemical Intrusion

Some of the many causes of chemical intrusion (in addition to condenser leakage) include:

- Makeup water system malfunction
- Chemical cleaning residue; acid, caustic, other
- Maintenance chemicals and preservatives

Minor chemical intrusions can be controlled by employment of idle condensate polishers, if available. Otherwise, immediate shutdown of the unit is required to protect the once through evaporator circuit and all steam touched components.

Shutdown should be followed by draining and flushing the unit. Inspection of critical areas of the system (evaporator circuits, superheater, turbine, etc.) should be performed to assess the effects of chemical intrusion on the system. Chemical cleaning of the affected components may be required, depending on the results of the inspection. Equipment repairs may be required. In such case, a longterm layup will be required. (See discussion in Section 3.2.)

During emergency shutdowns such as for major cooling water leaks and extensive chemical contamination, immediate unit shutdown is required. Therefore, little can be done to adjust cycle chemistry during shutdown, since rapid action is required. During such occasions, the unit should be drained, flushed and inspected to assess damage, as outlined previously. Restarting the unit will be contingent upon this inspection, as will layup provisions.

4.5 Caustic Treatment for Drum HRSG Circuits

Use of caustic treatment (CT) in drum type evaporators provides protection against feedwater contamination. In high pressure evaporator circuits, it is very important to measure the carryover to verify that the treatment will not contaminate the steam. Caustic is very corrosive to turbines and steam purity must be monitored carefully, as described in the HRSG Cycle Chemistry[(2)] guidelines.

Sodium hydroxide does not normally exhibit hideout and return properties as is often observed when using PC. No adjustment in the evaporator chemistry is needed prior to short term shutdown. As stated in earlier sections of this report, the preferred practice shut down with the optimum operating chemistry. Feedwater pH should be kept in limits with addition of ammonia.

During short term shutdown, the unit should be bottled up under a nitrogen cap or pressurized by with auxiliary steam. Performed properly, this will minimize air intrusion effects, including pH depression by carbon dioxide. Long shutdowns require protection by one of the methods indicated in Section 3.

The basic considerations outlined in Sections 4.2 and 4.3 for PC and AVT also apply during shutdown for evaporator circuits using caustic treatment (CT), with the addition that special care has to be taken to prevent any carryover of sodium hydroxide from the evaporator water, as this could lead to stress corrosion of austenitic components in the steam circuits.

A road map for shutdown of a drum HRSG unit with an all-ferrous feedwater heating system operation with CT is given in Figure 4-4. The time taken to achieve stable shutdown conditions will be plant dependent. This should be determined for each unit, used as guidance for subsequent repeat operations and amended in the light of operating experience. The road map can be divided into five steps.

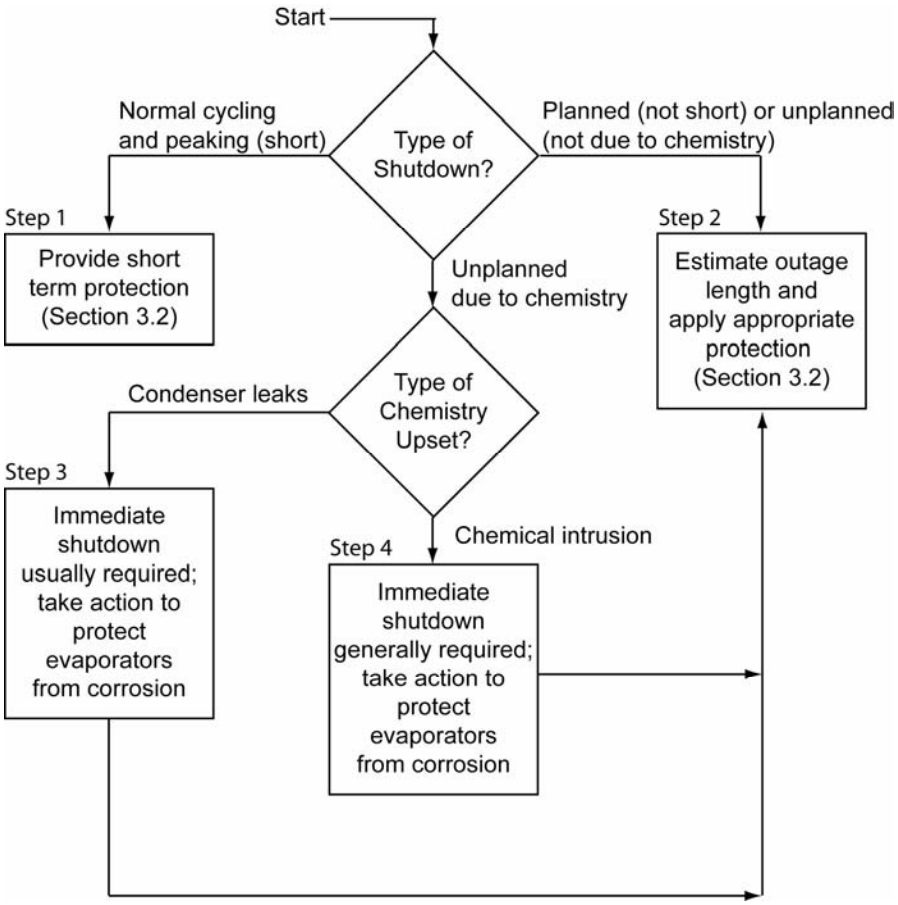


Figure 4-4
Road Map for Shutdown of Combined Cycle Units with Drum Type Evaporator HRSG Circuits using Caustic Treatment (CT)

The steps are essentially similar to those described for AVT (Section 4.3).

Step 1 – Normal Cycling or Peaking: Load Reduction or Shutdown

Normal cycling or peaking load reduction or shutdown presumes a short term shutdown and use of protection measures as described in Section 3.2 and Step 1 of the Figure 3-1 road map.

An orderly reduction of load can be performed for routine cycling operations. Also, an orderly reduction of load or unit shutdown can be performed when contamination is minimal, as determined by chemical monitoring during such transients.

During orderly load reductions, the feedwater and evaporator water chemical limits should be adjusted to conform with the HRSG Cycle Chemistry Guidelines[2] and for drum evaporator units and the latest CT Guidelines.[3]

Particular care should be exercised to monitor unit conditions (temperatures and pressures plus condenser vacuum) during the shutdown so as to prevent air ingress; action should be taken to

provide another form of protection before this occurs. Blowdown should be maintained at an appropriate level to remove contaminants from the system.

Step 2 – Outages

Duration of planned or unplanned outages will depend on system demand or the extent of the work required before returning the unit to operation. The length of time required for maintenance must be estimated and, depending on this estimate, an appropriate layup should be initiated. For longer wet layups, adjustment of chemistry prior to shutdown may be desirable. See Section 3.2 discussion and Figure 3-1.

An unplanned outage due to an equipment or system failure can be treated as for a planned outage.

Step 3 – Chemical Transients: Condenser Leak

The level of contamination in the cycle is dependent on both the amount of cooling water ingress (size and number of leaks) and, usually more importantly, the cooling water dissolved solids concentration. Evaporator water pH control is critical and monitoring condensate cation conductivity and sodium levels will assist in estimating the magnitude of the leak. The addition of extra sodium hydroxide may be required, if the evaporator water pH drops. Immediate shutdown of the unit is required if the evaporator water pH falls below 8.

Chemistry monitoring is especially important when a condenser leak is suspected to be developing and the cooling water is a high solids water such seawater, brackish water or high solids cooling tower water. Without condensate polishing (as is usually the case), evaporator water pH is impossible to control in such cases and immediate shutdown is required because, with continued operation, serious damage can occur to evaporator tubes within a short period of time.

On units with condensate polishing, there is greater flexibility in dealing with leaks that do not rapidly depress the evaporator pH to levels requiring immediate shutdown; unit shutdown can generally be accomplished in a more orderly fashion.

For small condenser leaks in units using fresh, relatively low dissolved solids cooling water, it may be possible to avoid shutdown when the HRSG consists of drum evaporator circuits only; however a load reduction would be needed. Avoidance of shutdown requires: effective chemistry instrumentation to identify the leak promptly; the ability to rapidly and effectively isolate the area of the condenser experiencing leakage (divided waterbox design); and reliable identification and plugging of all leaking tubes. It cannot be overemphasized that such action will be successful only if rapid leak detection results in immediate action to reduce load and isolate the condenser. Evaporator chemistry must be watched very closely if in-service assessment and repairs are attempted; it may be necessary to take actions such as reducing pressure, blowing down and addition of extra sodium hydroxide to the evaporator water. If evaporator chemistry cannot be controlled, the unit should be shut down promptly, and the leaks isolated and repaired.

Generally, the unit should be shut down to repair the condenser leak.

Substantial intrusion of any cooling water, such as may follow mechanical damage of several tubes within the condenser, into the HRSG will require that the unit be shut down immediately. It should then be drained, flushed and refilled with condensate quality water plus chemicals consistent with operating requirements of CT chemistry.

Step 4 – Chemical Transients: Chemical Intrusion

Some of the many causes of chemical intrusion (in addition to condenser leakage) include:

- Makeup water system malfunction
- Chemical cleaning residue; acid, caustic, other
- Maintenance chemicals and preservatives

Minor chemical intrusions can be controlled by increasing evaporator blowdown.

More serious chemical intrusions may affect (lower) the evaporator circuit pH, necessitating adjustment of pH through the addition of a further 1-2 ppm of sodium hydroxide. If these treatments are unsuccessful, the unit must be shut down if the pH falls below 8[(2)]. The unit then requires careful inspection to determine possible damage, and the necessity for repair and possible chemical cleaning prior to restart.

Intrusion of chemical contamination requires immediate unit shutdown, draining and flushing the unit. Inspection of critical areas of the system (evaporator circuits, superheater, turbine, etc.) should be performed to assess the effects of the chemical intrusion. Chemical cleaning may be required, depending on the results of the inspection. Equipment repairs may be required. In such case, a longterm layup will be required (See Section 3.2).

During emergency shutdowns, such as for major condenser leaks and extensive chemical contamination, immediate unit shutdown is required. Therefore, little can be done to adjust cycle chemistry during shutdown, since rapid action is required. During such occasions, the unit should be drained, flushed and inspected to assess damage, as outlined previously. Restarting the unit will be contingent upon this inspection, as will layup provisions.

4.6 Oxygenated Treatment For Drum HRSG Circuits

With oxygenated treatment (OT), careful control of the cation conductivity of the feedwater and evaporator water is required. [(5)] Increases in the cation conductivity in the presence of oxygen can result in corrosive conditions, and thus require immediate attention. Thus, consistent with practice in conventional boilers using OT, it is necessary to stop oxygen feed at least one hour prior to shutdown. Depending on the expected duration of the shutdown, the pH may also be adjusted through addition of ammonia. These actions, in combination with any needed changes in unit operation result in AVT chemistry conditions in the cycle. The only exception is that the pH need not be increased for short term shutdowns.

As with drum type evaporator circuits treated with AVT, blowdown is available to control concentrations of the low levels of impurities normally present; however, when feedwater contamination enters the evaporator, there is no corrosion protection and the pH will fall rapidly. In drum type evaporator circuits using OT chemistry, the pH will begin to fall almost immediately, often serving as the first indication of contamination. Immediate shutdown of the unit is required if the evaporator water pH falls below 8. Addition of trisodium phosphate or sodium hydroxide will help minimize corrosion damage.

Short term shutdown guidance for OT[5] consists of stopping oxygen feed at least one hour before shutdown of the unit. Deaerator vents, if furnished, should be opened, and venting increased to aid in cycle deaeration in conjunction with stopping oxygen feed. Shutdown of ammonia feed occurs simultaneously with unit shutdown.

Intermediate, longterm and extended shutdown guidance[5] consists of stopping oxygen feed at least one hour before shutdown of the unit and of increasing ammonia feed rates. Simultaneously, the deaerator vents, if furnished, should be opened or the deaerator venting should be increased to aid in cycle deaeration in conjunction with stopping oxygen feed. The object of the increase in ammonia feed rates is to achieve a pH higher than 9.0 in the HRSG evaporator water (downcomer) of all individual circuits.

In other respects, the shutdown is essentially the same as outlined in the road map for a drum evaporator circuit operated on AVT Figure 4-4, as discussed in Section 4.3.

4.6.1 Shutdown Procedures

Hydrazine and other reducing agents should never be utilized in HRSG circuits operating on OT. The first guiding principle (see Section 2.3), clearly indicates that adding such treatments at shutdown or during layup is inadvisable, as such action would change the potential of the water. The preferred practice is to stop the oxygen feed at least one hour before shutdown and, for longterm and extended shutdowns, to increase the pH in the cycle. Oxygen addition must be stopped for all types of shutdowns. In order to exclude the possibility of oxygen in-leakage into the shutdown unit by way of leaking valves, a physical disconnection of the oxygen supply from the oxygen dosing line is advised.

4.6.2 Short Term Shutdown

Figure 4-5 graphically depicts guidance for short term shutdown. The guidance[5] consists simply of stopping oxygen feed at least one hour before shutdown of the unit. Deaerator vents (if furnished) should be opened, to aid in cycle deaeration in conjunction with stopping oxygen feed. At the same time, any feedwater heaters (if furnished) should be carefully vented. Shutdown of ammonia feed should occur simultaneously with unit shutdown.

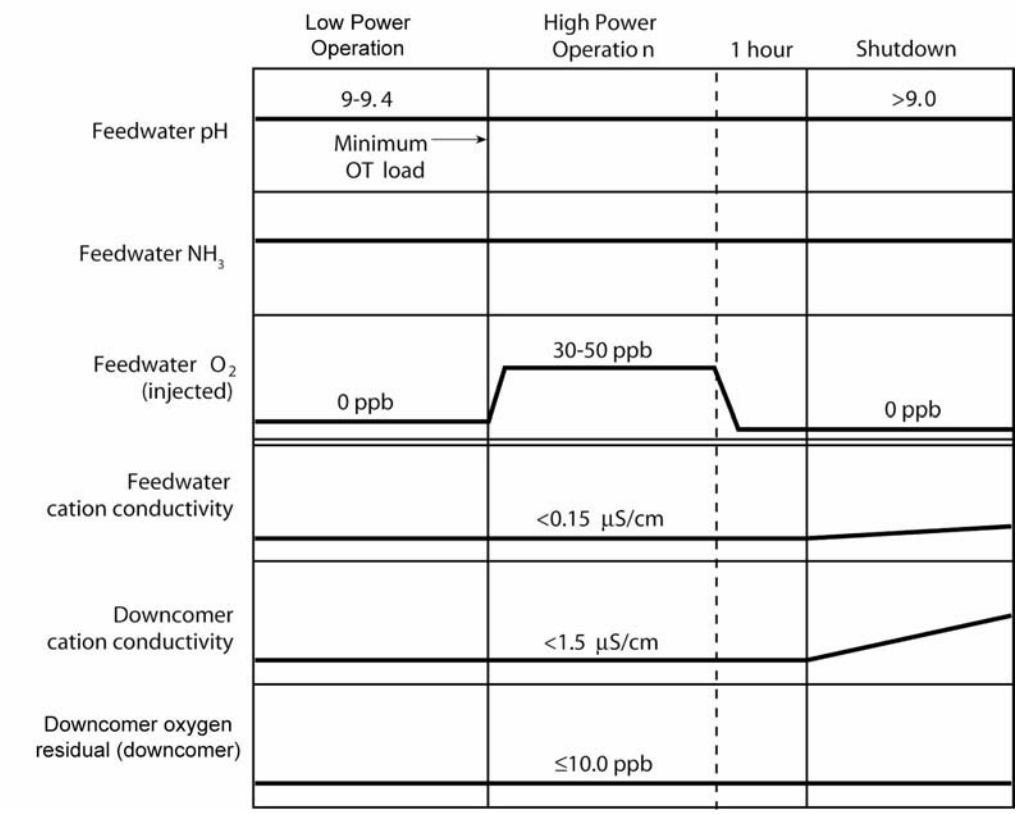


Figure 4-5
Shutdown Chemistry Guidance for Drum Type Evaporator Circuits using OT Chemistry: Short Term Shutdowns

4.6.3 Intermediate, Longterm and Extended Shutdown

Figure 4-6 graphically depicts guidance for longterm and extended shutdown. The guidance[5] consists of stopping oxygen feed at least one hour before shutdown of the unit and of increasing ammonia feed rates. Simultaneously, the deaerator vents (if furnished) should be opened to aid in cycle deaeration in conjunction with stopping the oxygen feed. At the same time, the heaters (if furnished) should be carefully vented. The object of the increased ammonia feed rate is to achieve a pH higher than 9.0. Protection then follows as indicated in Section 3.2 and on the Figure 3-1 roadmap.

Then, both the oxygen level in the entire cycle and the cycle pH are comparable with those typical for AVT (feedwater oxygen <10 ppb and pH >9.0). During the longterm shutdown, the cycle can be regarded and treated as a cycle operated on AVT[2, 4]. The only exception is the already mentioned elimination of the hydrazine or other reducing agent dosing even for a wet layup. (Use of reducing agents is only permissible in those few combined cycles with copper alloys in the feedwater systems that need to operate on AVT(R), reducing all volatile treatment.)

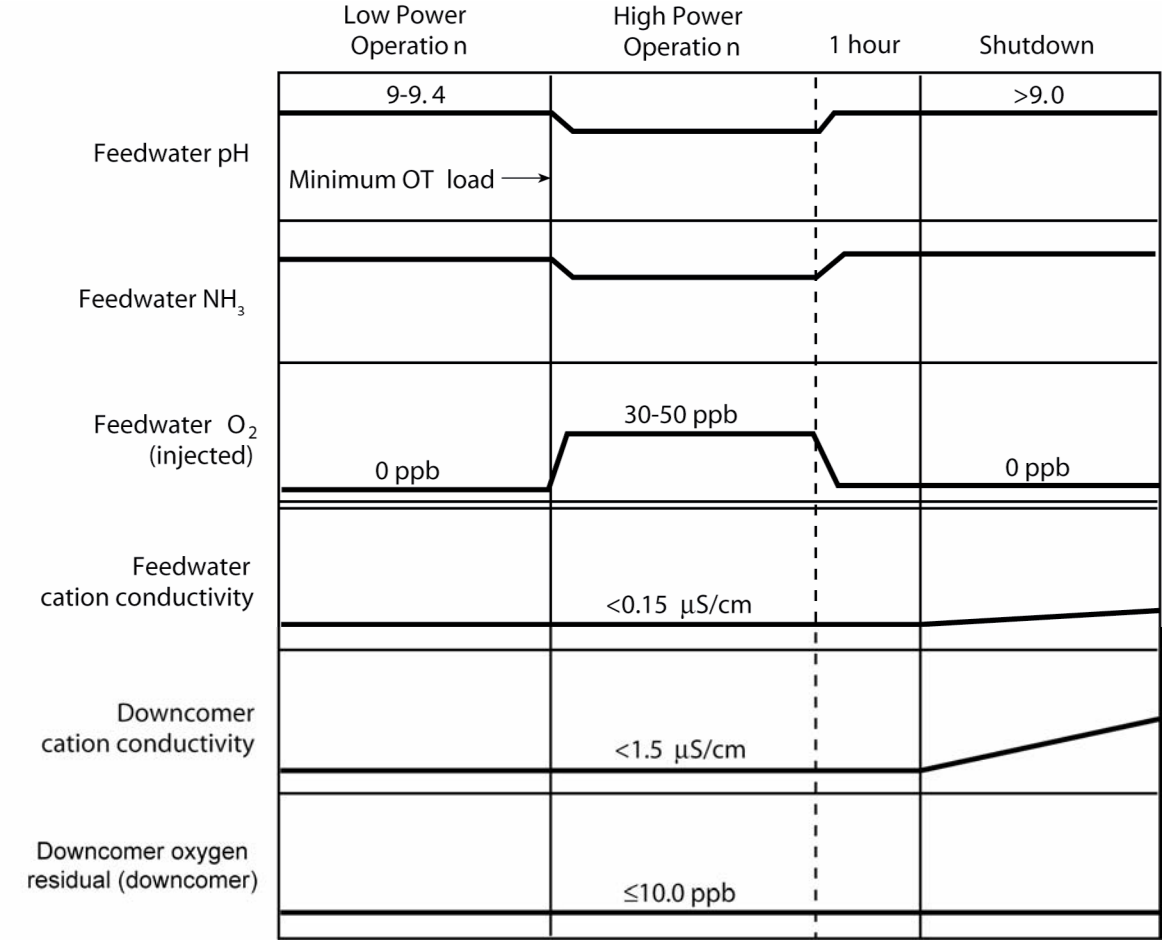


Figure 4-6
Shutdown Chemistry Guidance for Drum Type Evaporator Circuits using OT Chemistry: Intermediate, Longterm and Extended Shutdowns

4.6.4 Emergency Shutdown

In case of an emergency shutdown for reasons of a technical fault (e.g., defects in the electrical equipment, an HRSG tube failure), the unit is shut down with the optimum operating chemistry. If it is foreseeable that the unit will be brought back into service very fast (e.g., overnight or over a weekend), additional chemical measures are unnecessary. In case the shutdown will continue for a longer period of time (e.g., several days or longer), the replacement of oxygen containing water with an oxygen free (<10 ppb oxygen) ammonia treated water (pH >9) makes sense. Customary layup procedures (Section 3) have to be employed for prolonged shutdowns.

4.6.5 Shutdown as a Result of a Serious Chemistry Excursion

During emergency shutdowns, such as for major condenser leaks and extensive chemical contamination, immediate unit shutdown is required. Therefore, little can be done to adjust cycle chemistry during shutdown, since rapid action is required. During such occasions, the unit should

be drained, flushed and inspected to assess damage, as outlined previously. Restarting the unit will be contingent upon this inspection, as will layup provisions.

4.7 Oxygenated Treatment for Once-Through HRSG Circuits

Only a limited number of HRSGs include once-through evaporator circuits; in many cases, the feedwater to this circuit is provided by a low pressure evaporator. The design includes a condensate polisher or filter in some but not all cases; this equipment, when present, may only be sized to handle full flow during startup of the unit.

With oxygenated treatment (OT), careful control of the cation conductivity of the feedwater and evaporator water is required. [5] Increases in the cation conductivity in the presence of oxygen can result in corrosive conditions, and thus require immediate attention. Thus, consistent with practice in conventional boilers using OT, it is necessary to stop oxygen feed at least one hour prior to shutdown. Depending on the expected duration of the shutdown, the pH may also be adjusted through addition of ammonia. These actions, in combination with any needed changes in unit operation result in AVT chemistry conditions in the cycle. The only exception is that the pH need not be increased for short term shutdowns.

Most of the guidance given in Section 4.6 for units with drum type evaporators using oxygenated treatment (OT) is also applicable to once-through units. As in all once-through evaporators control of evaporator water purity cannot be achieved by blowdown; any impurities that do not form deposits in the evaporator circuit will enter the steam path. Thus contamination incidents normally require immediate shutdown to protect the superheater and reheater circuits and the steam turbine. Protection of the turbine is vitally important following such events.

4.7.1 Shutdown Procedures

Hydrazine and other reducing agents should never be utilized in units operating on OT. The first guiding principle (see Section 2.3), clearly indicates that adding such treatments at shutdown or during layup is inadvisable, as such action would change the potential of the water. The preferred shutdown practice is to stop the oxygen feed at least one hour before shutdown and, dependent on anticipated shutdown duration shutdown, to increase the pH in the cycle. Oxygen addition must be stopped for all types of shutdowns. In order to exclude the possibility of oxygen in-leakage into the shutdown unit by way of leaking valves, a physical disconnection of the oxygen supply from the oxygen dosing line is advised.

In many respects, the shutdown considerations are essentially the same as outlined in the road map for a once-through evaporator circuit operated on AVT Figure 4-5, as discussed in Section 4.4. However, action must first be taken to modify the chemistry (secure oxygen feed and adjust ammonia feed if needed) and unit operations (system vents) prior to shutdown.

4.7.2 Short Term Shutdown

Figure 4-7 graphically depicts guidance for chemistry adjustments required for short and intermediate term shutdowns where the pressure does not decay to atmospheric or oxygen will be excluded from the water by other means. Guidance[5] consists simply of stopping oxygen feed at least one hour before shutdown of the unit. Deaerator vents (if furnished) should be opened to aid in cycle deaeration in conjunction with stopping the oxygen feed. At the same time, any heaters (if furnished) should be carefully vented. Shutdown of ammonia feed should occur simultaneously with unit shutdown.

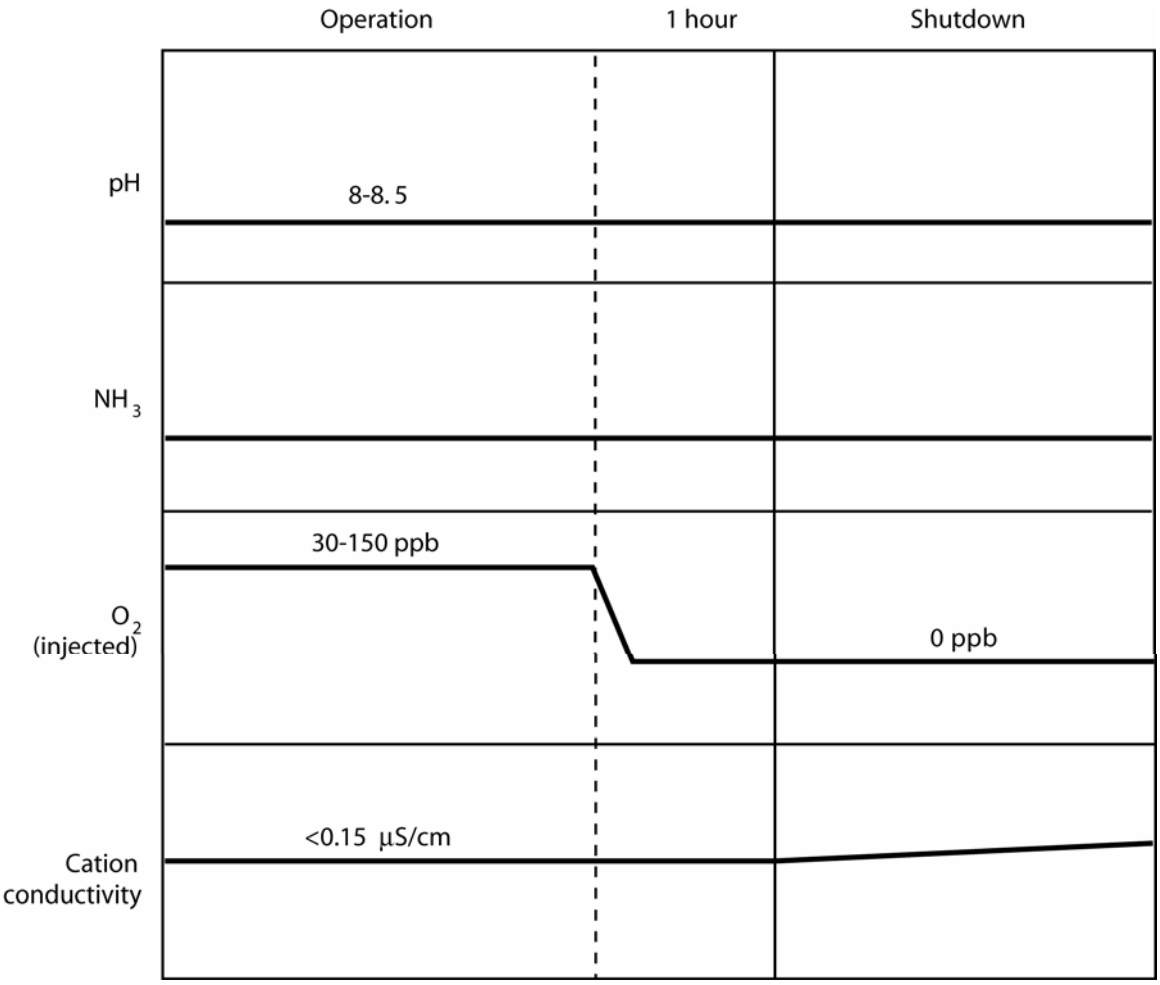


Figure 4-7
Shutdown Chemistry Guidance for Once-Through Evaporator Circuits using OT Chemistry: Short Term Shutdowns

4.7.3 Intermediate, Longterm and Extended Shutdown

Figure 4-8 graphically depicts guidance for longterm and extended shutdowns. The guidance[5] consists of stopping oxygen feed at least one hour before shutdown of the unit and of increasing ammonia feed rates. Simultaneously, the deaerator vents (if provided) should be opened to aid in

cycle deaeration in conjunction with stopping the oxygen feed. At the same time, any heaters should be carefully vented. The object of the increased ammonia feed rates is to achieve a pH higher than 9.0 in agreement with AVT chemistry guidelines[2, 4].

Then, both the oxygen level in the whole cycle and the cycle pH are comparable with those typical for AVT (feedwater oxygen <10 ppb and pH >9.0). During the shutdown, the cycle can be regarded and treated as a cycle operated on AVT[2, 4]. Protection then follows as indicated in Section 3.2 and on the Figure 3-1 roadmap.

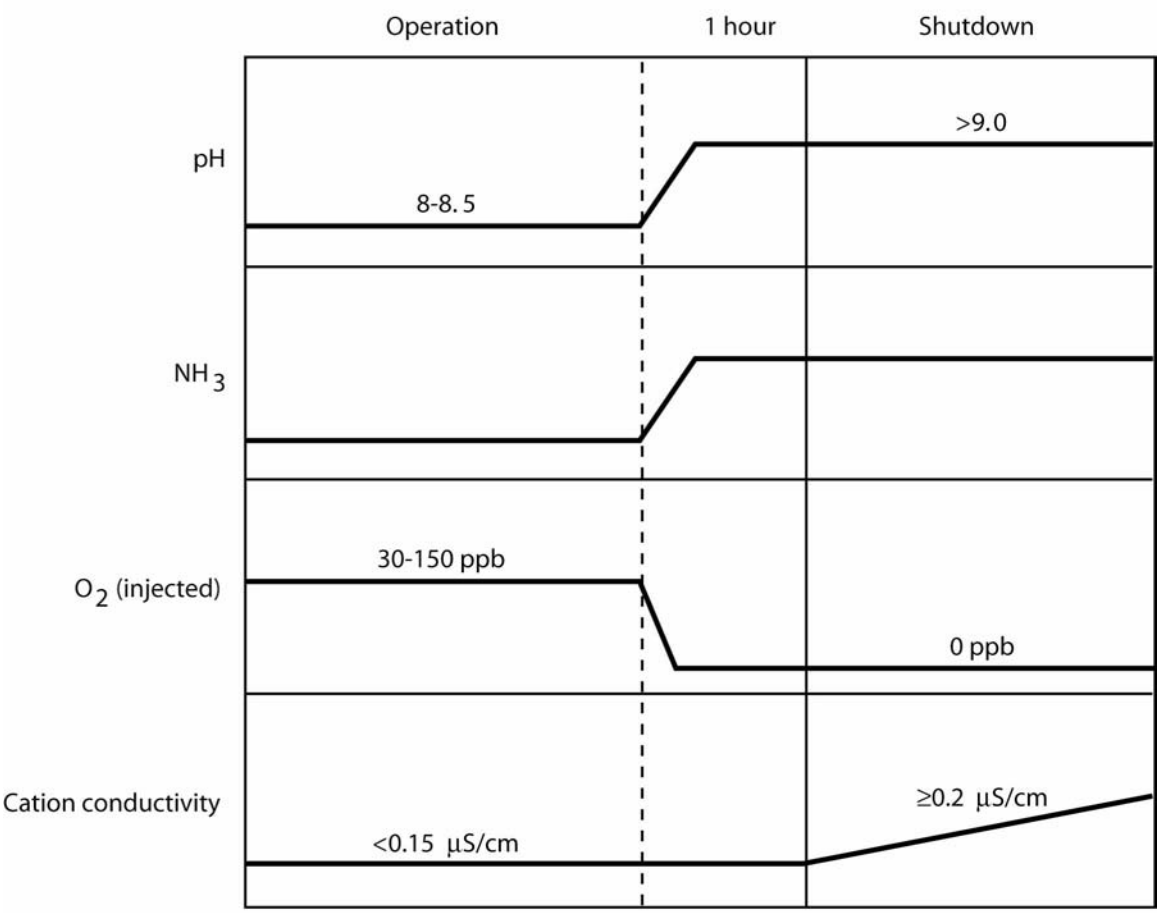


Figure 4-8
Shutdown Chemistry Guidance for Once-Through Evaporator Circuits using OT Chemistry: Intermediate, Longterm and Extended Shutdowns

4.7.4 Emergency Shutdown

In case of an emergency shutdown for reasons of a technical fault (e.g., defects in the electrical equipment, an HRSG tube failure), the unit is shut down with the optimum operating chemistry. If it is foreseeable that the unit will be brought back into service very fast (e.g., overnight or over a weekend), additional chemical measures are unnecessary. In case the shutdown will continue for a longer period of time (e.g., several days or longer), the replacement of oxygen containing water with an oxygen free (<10 ppb oxygen) ammonia treated water (pH >9) makes sense. Customary layup procedures (Section 3) have to be employed for prolonged shutdowns.

4.7.5 Shutdown as a Result of a Serious Chemistry Excursion

During emergency shutdowns, such as for major condenser leaks and extensive chemical contamination, immediate unit shutdown is required. Therefore, little can be done to adjust cycle chemistry during shutdown, since rapid action is required. During such occasions, the unit should be drained, flushed and inspected to assess damage, as outlined previously. Restarting the unit will be contingent upon this inspection, as will layup provisions.

4.8 References

1. Delivering High Reliability Heat Recovery Steam Generators. EPRI, Palo Alto, CA: March 2003. 1004240.
2. *Cycle Chemistry Guidelines for Combined Cycle/Heat Recovery Steam Generators (HRSGs)*. EPRI, Palo Alto, CA: 2003. 1010438.
3. *Cycle Chemistry Guidelines for Fossil Plants: Phosphate Continuum and Caustic Treatment*. EPRI, Palo Alto, CA: January 2004. 1004188.
4. *Cycle Chemistry Guidelines for Fossil Plants: All-Volatile Treatment*. EPRI, Palo Alto, CA: November 2002. 1004187.
5. *Cycle Chemistry Guidelines for Fossil Plants: Oxygenated Treatment*. EPRI, Palo Alto, CA: March 2003. 1004925.

5
STARTUP FOR VARIOUS CYCLE CHEMISTRIES

5.1 Startup Requirements for the Various Cycle Chemistries

A recent EPRI publication[(1)], covering the operational aspects of heat recovery steam generators necessary to achieve high reliability, notes that for rapid startups, it is essential to have auxiliary steam to increase condenser vacuum before the unit is fired. This is necessary in order to permit use of the high pressure (HP) and hot reheat (HRH) steam bypass systems to control the HP and HRH pressures shortly after HP steam generation commences. It also affords an opportunity to check steam purity prior to admission of steam to the turbine.

Early use of the bypasses is also essential to establish cooling flows through the HP superheater and reheater circuits and then regulate the rate of increase in HP pressure to safely limit the rate of heating of the thick HP steam drum. During this period, and until the transfer of all steam to the steam turbine is concluded later in the startup, the HRH steam is conditioned and dumped to the condenser to preserve demineralized water. Auxiliary steam from an auxiliary boiler or from another operational unit is required to seal the steam turbine glands and raise condenser vacuum.

For satisfactory chemical operation during startup, it is necessary to prevent excessive oxygen ingress. The use of deaerated makeup will appreciably reduce oxygen levels during startup. Air in-leakage must be controlled as additional parts of the heat cycle are under vacuum during low load operation. Information on measurement and detection of air in-leakage is included in Appendix C. Use of auxiliary steam to peg the deaerator (if part of the design) will enhance oxygen removal at this point in the cycle.

Detection and repair of condenser leaks during startup is critical to prevent ingress of harmful contaminants such as chlorides and sulfates. Condensate polishers can help decrease startup times but are not commonly provided on combined cycle units.

Also, very few combined cycle plant feedwater cycles include feedwater heaters. When present, it may be desirable to discard heater drains during initial startup operations to reduce the amount of iron (and copper, if present) entering the HRSG. If the shutdown and layup of the unit are properly controlled, heater drains should clear more quickly, than with unprotected shutdowns.

As most combined cycles do not include copper in the feedwater system, oxidizing all volatile treatment, AVT(O), is suitable for the majority of units, while a few may be able to operate beneficially with oxygenated treatment (OT). Reducing agents should not be added in cycles employing these feedwater treatments and ensuing discussions of startup reflect this. (Only units

with copper in the feedwater system should apply a reducing agent such as hydrazine to establish reducing AVT conditions.)

If the HRSG has been stored under nitrogen or filled with ammonia solution, it is necessary to ensure that this is safely vented or disposed.

Initial startup depends on the layup procedure. If the layup was short term, and the unit was filled with water treated for typical normal operations, startup can proceed without delay. If the feedwater system was full of water treated for a longer term layup, as shown in the road map, Figure 3-1 in Section 3.2, some water may have to be dumped to reduce ammonia to more appropriate values.

If the unit was laid up dry, the feedwater system and HRSG water touched circuits must be filled with deaerated high purity water and treated with chemicals (ammonia) to correspond to the normal operating conditions practiced on that unit.

Startup monitoring is largely accomplished by use of the core instrumentation for each chemistry as outlined in the EPRI Cycle Chemistry Guidelines for Combined Cycle/Heat Recovery Steam Generators (HRSGs).[(2)] At startup, the feedwater may include high levels of iron and silica, particularly following maintenance outages. Most of the iron and silica often will be present in the condensate as the surface area of the feedwater system is not extensive. Also, feedwater pH must be controlled by adjustment of ammonia feed rate thus monitoring of parameters such as pH, specific conductivity and ammonia consistent with plant capabilities and practices is useful. Evaporator pressure in drum circuits must be carefully controlled to avoid carryover. Silica, though not a core parameter, can be troublesome as it can transport to steam and foul the low pressure turbine during and following startup, so this parameter should also be monitored during startup.

During early startup, the HRSG feedwater should be closely monitored. The following limits for the HRSG feedwater should be met before startup:

- Oxygen <100 ppb
- Iron <100 ppb (<30 ppb if the HRSG includes a once-through circuit)
- Silica <50 ppb (<30 ppb if the HRSG includes a once-through circuit)

By following the guidelines and procedures outlined in this section, the concentrations can be reduced to less than those shown above. Further, the initial measured values should fall as the startup progresses. Good control will require close compliance with the guidance for shutdown and layup given in Sections 3 and 4.

During startup, monitoring of the condensate and feedwater must be continued, as well as the chemistry conditions in all drum evaporator water circuits and steam from all evaporators. EPRI Cycle Chemistry Guidelines for Combined Cycle/Heat Recovery Steam Generators (HRSGs)[(2)] set drum evaporator chemistry limits on the basis of pressure and apply to operating pressures of 600 psi (4.1 MPa) and greater; chemistry in drum evaporator circuits with lower design operating pressures should comply with target values for operation at 600 psi (4.1 MPa).

It is also necessary to ensure that temperature ramps are maintained according to equipment manufacturer's specifications. Monitoring of corrosion product transport (essentially iron) can be used as a benchmark for assessment of the effectiveness of equipment protection measures. As the purpose of protection is to both minimize startup times and the total transport of iron to the HRSG, both grab samples (for startup time) and integrated corrosion product samplers (for cumulative mass transport assessment) may be useful. Such assessments are useful during early unit operations to establish baseline conditions and may be implemented as needed, to evaluate changes in iron transport during the life of the unit.

Evaporator drum pressure in each drum type circuit should remain at a reduced level until all chemistry limits for normal operation have been reached. Maximum use of blowdown (for drum-type evaporator circuits) and condensate polishing (if available) will minimize startup times. For drum type evaporator circuits any addition of trisodium phosphate and/or sodium hydroxide has to be carefully controlled to ensure that excessive carryover into the steam does not occur. This is important in cycle designs that do not include a steam bypass system. Operation at reduced pressures is needed until steam purity and chemistry around the cycle is under control.

The various methods of chemical conditioning of evaporator water are considered in the following sections in the same order as they appear in the recently revised *Cycle Chemistry Guidelines for Combined Cycle/Heat Recovery Steam Generators (HRSGs)*[(2)].

Since, in some cases, the evaporator circuits of multi-pressure HRSGs may operate on different chemistries and HRSGs also may include both drum-type and once-through circuits, operators should consider all of the sections which follow that are relevant to the HRSG of interest, to ensure that customized startup procedures developed comply with the guiding principles of Section 2.3, as well as the requirements of Sections 5.2 to 5.7 which follow.

5.2 Startup of Units with Phosphate Continuum (PC) Treatment of Drum HRSG Circuits

The recently revised HRSG Cycle Chemistry Guidelines[(2)] contain pressure curves and action levels which relate various chemical parameters to evaporator circuit operating pressure. During startups, the initial lower drum pressure permits evaporator water chemical concentrations to be higher than during normal operation. Also, the cumulative operating hours per year for which the various action levels can be exceeded are twice the values for cycling units as compared to base loaded units. The values are specific to low and high level phosphate continuum (PC) treatments, PC(L) and PC(H).

The ramp to full pressure with a cold start is dependent on component design and stress limitations. Frequent analysis of the feedwater and evaporator water with early emphasis on suspended solids and silica is recommended. Suspended solids are a measure of the iron oxide inventory and the source of deposition and possible subsequent underdeposit corrosion. Silica, which is most likely to be present after maintenance activity, is monitored out of concern for turbine deposition.

Units with HRSG evaporator circuits using PC chemistry should be managed as follows.

- Adjust evaporator chemical feed to take advantage of tolerance for higher alkalinity at lower pressure.
- Adjust trisodium phosphate feed to support anticipated blowdown rate.
- The use of conductivity measurements will provide an indirect assessment of phosphate concentrations.
- Anticipate HRSG startup and begin dosing chemicals so that target treatment is in place when HRSG is fired.
- Maximize blowdown and perform bottom blow (if available) during startup when solids are at their highest concentration.
- With pressure increases above 600 psi (4.1 MPa) when PC is used in a high pressure circuit, the phosphate residual should be controlled to a concentration consistent with the HRSG Cycle Chemistry Guideline[(2)] values for phosphate versus pressure for PC(L) or PC(H) as apply.
- Operate deaerator vents as needed to prevent air ingress, consistent with plant design and availability of auxiliary steam during startup.
- Use makeup water that has low dissolved oxygen levels.

Transition to normal operation may proceed as follows.

- Continue blowdown reduction in 50% increments.
- Adjust phosphate chemical feed to support measured or estimated blowdown rate.
- Increase trisodium phosphate to increase alkalinity. (Monosodium phosphate and disodium phosphate should not be added with PC chemistry.) In the case that the pH is too high, then the appropriate action is to increase the blowdown rate.
- Be precise in measuring chemical feed dose.
- Monitor chemical feed pump performance.
- Conserve blowdown since excess suspended solids have been removed, chemical feed is stable and consistent. Evaporator blowdown should be zero during normal operation with chemistry in limits.

During cold starts, in order to give added protection against contaminant ingress during the initial operation, the phosphate concentration may be adjusted to the maximum concentration permitted by the guidelines for PC. The pH should be maintained at the upper pH limit, adjusted for ammonia. Failure to account for positive bias of the pH due to the presence of ammonia will lead to inadequate chemistry. This can result in the HRSG actually operating below the PC control range and increase the risk of evaporator tube corrosion and failures.

The evaporator circuit may, if intended to normally operate on PC(L), can start up following the limits for PC(H) to provide additional chemical during early startup. As pressure increases, the limits of PC(L) should be applied, after the contamination levels are at or below the corresponding contaminant vs. pressure curves in the HRSG Cycle Chemistry Guidelines[(2)]. Heavy blowdown can be maintained throughout the startup until contaminant levels are well within limits, at which time the blowdown should be isolated. Sodium hydroxide dosing at low levels (1-2 ppm) can be used to ensure that the necessary pH is maintained even in periods with an increased blowdown. Avoid dryout in the evaporators and excess carryover of evaporator water into steam. The blowdown remains isolated during normal operation except in periods of abnormal contamination.

Depending on the plant, and the shutdown and layup conditions adopted, several steps will be required for startup (in addition to filling the HRSG following a long shutdown and safely venting the nitrogen, if used). The steps used during startup will be plant specific and, depending on the practicality, the following stages should be monitored carefully, at least during a trial period:

- Feedwater to HRSG, with emphasis on purity and ammonia dosing control
- Pressure raising in HRSG, with emphasis on chemistry control in drum evaporator circuits
- Steam from HRSG circuit, with emphasis on carryover, steam purity and feedwater purity
- Steam to turbine, with emphasis on carryover, steam purity and feedwater purity
- Load raising, with emphasis on attaining limits for full load operation

Operating personnel should avoid making changes to evaporator chemistry in reaction to chemistry changes following a unit trip (such as depressed or elevated pH). This chemistry change is normal and is usually the result of chemical "hideout" and "return" phenomena. Careful evaluation of the trip induced chemistry changes is necessary and it is important to avoid "chasing" or making frequent adjustments in chemistry in response to such changes. Proper dosing of phosphate as allowed under PC and the exclusive use of trisodium phosphate (plus sodium hydroxide if required to maintain pH) tends to minimize these changes. As a rule, any phosphate hideout return causes a pH increase when only trisodium phosphate is added to the evaporator circuits.

A road map for startup of units with circuits employing PC is given in Figure 5-1.

The road map for startup with phosphate continuum, Figure 5-1, can be divided into five steps:

Step 1 – System Stored Dry (Dehumidified Air or Nitrogen)

If the system has been stored dry (Section 3.2), it should be filled with deaerated water which meets the HRSG Cycle Chemistry Guidelines for phosphate continuum treated circuits[(2)].

Step 2 – System Stored Wet

If the system has been stored wet with a surplus of ammonia and a nitrogen cap as indicated in Section 3.2, it must be drained under nitrogen and refilled with deaerated water meeting the HRSG Cycle Chemistry Guidelines for phosphate continuum[2]. The startup of the unit can then proceed.

If the system is returning to service from a short term shutdown without changing the chemistry and has been protected as indicated in Section 3.2, it is allowable to proceed with startup of the cycle.

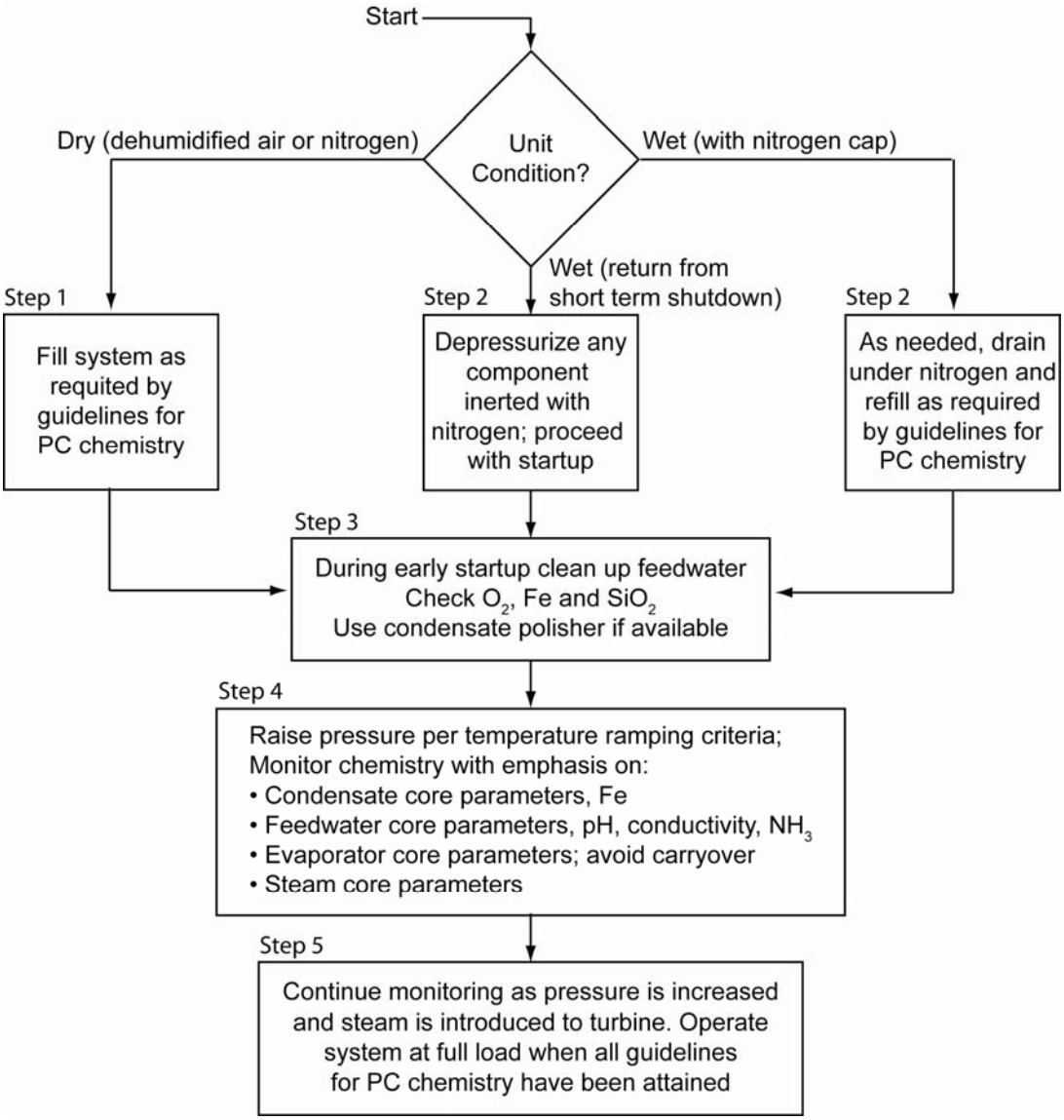


Figure 5-1
Road Map for Startup of Combined Cycle Units with Drum Type Evaporator HRSG Circuits Treated With Phosphate Continuum (PC) Chemistry

Step 3 – Feedwater Conditions

The following limits for the feedwater are required prior to raising pressure in the HRSG:

- Oxygen <100 ppb
- Iron <100 ppb
- Silica <50 ppb

During startup following major maintenance, the levels of corrosion products (iron) can be very high initially, especially if the unit has an air cooled condenser. Silica may also be a problem, particularly after maintenance activity. It is also useful to monitor these conditions in the condensate.

Feedwater dosing should be practiced as needed to meet control limits for ammonia.

Feedwater cleanup is possible in units equipped with condensate polishing. When these limits are attained, raising pressure in the HRSG evaporator circuits can begin consistent with limits for PC chemistry. Good control of feedwater in the early startup will require close compliance with the guidelines for unit shutdown and layup.

Step 4 – Chemistry Monitoring

After firing the HRSG, monitoring must be fully implemented, both for chemistry parameters, and to ensure that temperature ramps are maintained according to the equipment manufacturer's specifications.

During startup, the concentration vs. pressure curves can be utilized to control sodium, silica, chloride and sulfate. (Control figures for these constituents in evaporator water are included in the HRSG Cycle Chemistry Guidelines[2]). Evaporator circuit pressure should remain at reduced levels such that these limits are maintained before pressure can be increased to the next stage. Maximum use of blowdown will minimize startup times.

During startup, any chemical excursions must be dealt with quickly and effectively. Increases in feedwater sodium and cation conductivity may indicate contamination from the makeup system, contamination from inspection, cleaning and maintenance activities or, most likely, condenser leakage. The source must be found and the problem corrected at once. Excursions affecting (lowering) evaporator water pH must be corrected immediately by feeding additional trisodium phosphate or 1-2 ppm of sodium hydroxide. Avoid dryout conditions in the evaporators and excessive carryover of evaporator water impurities and conditioning chemicals into the steam.

Effects of cycle contamination are magnified at startup, due to relatively low flow rates for condensate, feedwater and steam. Cation conductivity may increase as a result of air ingress due to either aeration of water during the shutdown period or air in-leakage during startup. Shutdown and layup protection procedures conducted in accordance with the guiding principles of Section 2.3 will minimize these effects during ensuing startups. The change to evaporator water

chemistry will be minimal compared to contamination involving the makeup system, chemical cleaning activities or condenser leaks.

Step 5 – Full Load

Full load can be achieved when chemical limits are within the target values for normal operation given in the HRSG Cycle Chemistry Guidelines for phosphate continuum[2].

5.3 Startup of Units with All-Volatile Treatment (AVT) of Drum HRSG Circuits

If the evaporator water pH is depressed by contaminants, evaporator circuits can be started on phosphate continuum chemistry (Section 5.2) using trisodium phosphate additions only or with caustic treatment (Section 5.5) before gradually converting over to AVT. This period of adjustment permits the operating staff to ensure, by chemistry monitoring, that conditions are suitable for the establishment of AVT. The important overriding philosophy here is that chemicals (trisodium phosphate or sodium hydroxide) should not have to be added to the evaporator circuits on every startup when operating with AVT; in fact, such requirements are a possible indication that the chemistry selection is incorrect. Maximum use of blowdown may be required during startup to minimize contaminant levels in the HRSG. If the carefully controlled addition of trisodium phosphate or sodium hydroxide extends into the period where the unit is operating at full (or over) pressure, then special care should be taken that dryout in the evaporators or excessive carryover into the steam does not occur. Operation at reduced pressures may be preferable until cycle chemistry is under control.

During off-load conditions, impurities may have been released into the circuit or have entered from outside, e.g. condenser leaks, CO_2 with air ingress. Therefore, during startup, it is important to consider the effects of these on the feedwater, evaporator water and steam cation conductivity, silica, sodium, chloride and sulfate concentrations during startup. The oxygen concentration in the feedwater also requires special consideration. Restrictions will need to be applied to these parameters, but some relaxation from the normal HRSG Cycle Chemistry Guideline values[2] may be possible until steady state conditions are achieved.

During startups, the initial lower drum pressure permits evaporator water chemical concentrations to be higher than those at normal unit operating pressures. Also, the cumulative operating hours per year for which the various action levels can be exceeded are twice the values for cycling units, as compared to base loaded units.

It is important to prevent high concentrations of oxygen and chloride in the evaporator water, as these can act synergistically and may initiate corrosion[3]. For this reason, the oxygen concentration of the evaporator water should not be allowed to exceed 0.2 ppm during operation. It is also important to ensure that the pH, cation conductivity and chloride concentration are within the limits given in the HRSG Cycle Chemistry Guidelines[2] for evaporator water.

Depending on the plant, and the shutdown and layup conditions adopted, several steps will be required for startup (in addition to filling the HRSG following a long shutdown and safely venting the nitrogen, if used). The steps used during startup will be plant specific and, depending on the practicality, the following stages should be monitored carefully, at least during a trial period:

- Feedwater to HRSG, with emphasis on purity and ammonia dosing control
- Pressure raising in HRSG, with emphasis on chemistry control in drum evaporator circuits
- Steam from HRSG circuit, with emphasis on carryover, steam purity and feedwater purity
- Steam to turbine, with emphasis on carryover, steam purity and feedwater purity
- Load raising, with emphasis on attaining limits for full load operation

At full load, the normal values given in the HRSG Cycle Chemistry Guidelines[(2)] should be achieved. There may be room for relaxation, particularly, as regards silica in steam, during startup and the earlier stages of operation and during low load operation, provided the parameters are within the HRSG cycle chemistry action levels 1-3. The core parameters, sodium, cation conductivity and oxygen, given in the HRSG Cycle Chemistry Guidelines[(2)] should be monitored in the condensate, feedwater, evaporator water (preferably at downcomer) and steam. The normal operating levels, as given in the HRSG Cycle Chemistry Guidelines[(2)], should be achieved as soon as possible.

A road map for startup of a unit with drum type evaporator circuits operating on AVT is given in Figure 5-2. The time taken to achieve the required target values will be plant dependent. This should be determined for each unit, used as guidance for subsequent startups and amended in the light of operating experience. The procedure can normally be curtailed for warm and hot starts.

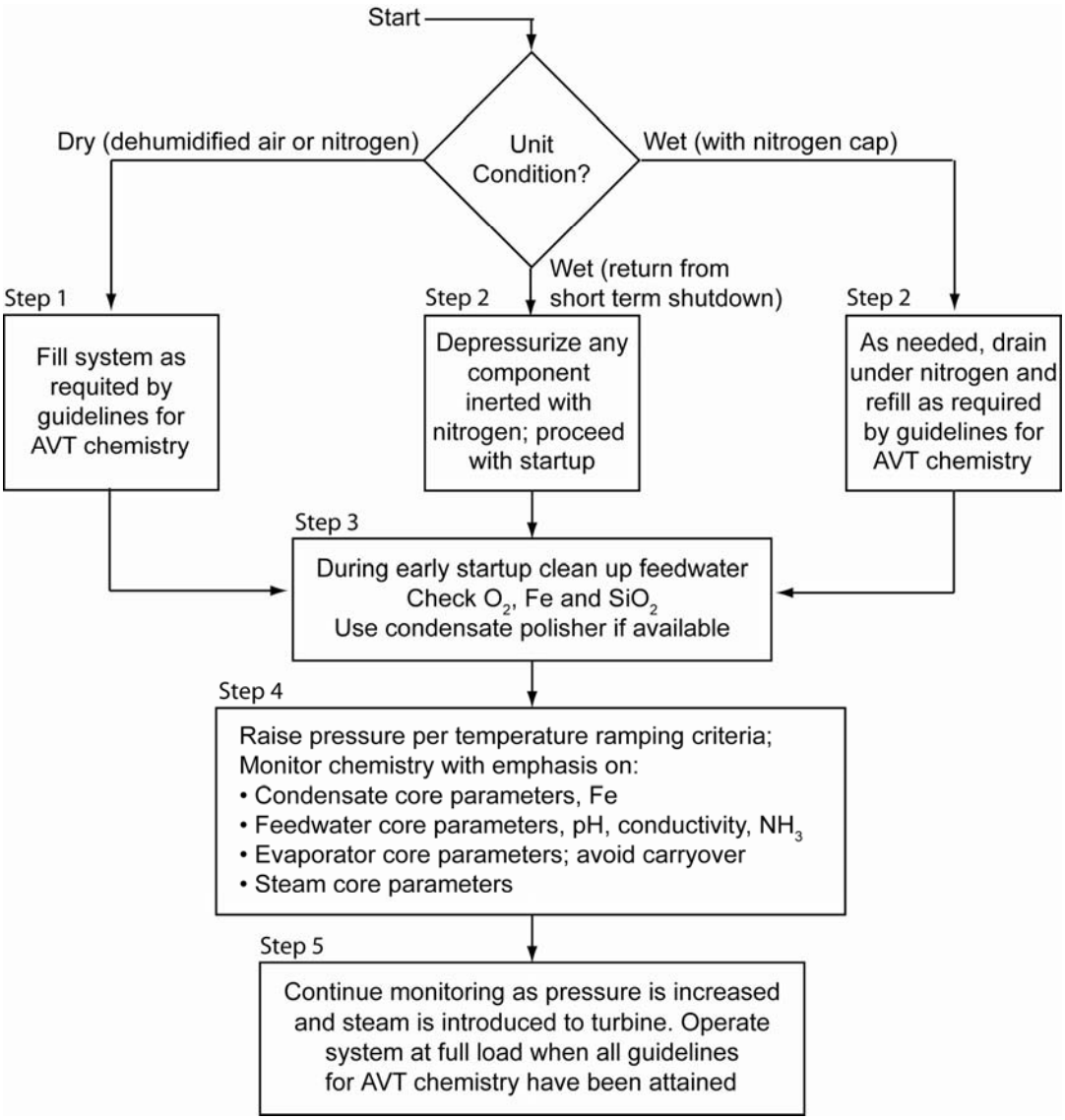


Figure 5-2
Road Map for Startup of Combined Cycle Units with Drum Type Evaporator HRSG Circuits Treated All Volatile Treatment (AVT) Chemistry

If the high purity feed and evaporator water conditions can not be maintained during startup, it may be necessary to resort to another form of chemical conditioning, such as phosphate continuum or caustic treatment. Operators using AVT should consult the sections of the guidelines, covering these chemistries if they are used during startup. The selection and optimization discussion in the HRSG Cycle Chemistry Guidelines[2] provides advice on determining the optimum evaporator water and feedwater choices for drum HRSG units.

The Figure 5-2 road map can be divided into five steps. The steps are essentially similar to those described for phosphate continuum treatment in Section 5.2. In drum-type evaporators operating on AVT, control of evaporator water purity can be achieved by blowdown in drum units.

Step 1 – System Stored Dry (Dehumidified Air or Nitrogen)

If the system has been stored dry (Section 3.2), it should be filled with deaerated water which meets the HRSG Cycle Chemistry Guidelines for drum type evaporator circuits operating on AVT[(2)].

Step 2 – System Stored Wet

If the system has been stored wet with a surplus of ammonia and a nitrogen cap as indicated in Section 3.2, it must be drained under nitrogen and refilled with deaerated water meeting the HRSG Cycle Chemistry Guidelines for drum type evaporator circuits operating on AVT[(2)].

If the system is returning to service from a short term shutdown without changing the chemistry and has been protected as indicated in Section 3.2, it is allowable to proceed with startup of the cycle.

Step 3 – Feedwater Conditions

The following limits for the feedwater are required prior to raising pressure in the HRSG:

- Oxygen <100 ppb
- Iron <100 ppb
- Silica <50 ppb

During startup following major maintenance, the levels of corrosion products (iron) can be very high initially, especially if the unit has an air cooled condenser. Silica may also be a problem, particularly after maintenance activity. It is also useful to monitor these conditions in the condensate.

Feedwater dosing should be practiced as needed to meet control limits for ammonia.

Feedwater cleanup is possible in units equipped with condensate polishing. When these limits are attained, raising pressure in the HRSG evaporator circuits can begin consistent with limits for AVT chemistry and equipment requirements for temperature ramping. Good control of feedwater in the early startup will require close compliance with the guidelines for unit shutdown and layup.

Step 4 – Monitoring

After firing the HRSG, monitoring must be fully implemented, both for chemistry parameters, and to ensure that temperature ramps are maintained according to the equipment manufacturer's specifications.

During startup, the concentration vs. pressure curves given in the HRSG Cycle Chemistry Guidelines[(2)] can be utilized to control conductivity, sodium, silica, chloride and sulfate. Evaporator pressure should remain at reduced levels such that these limits are maintained before

pressure can be increased to the next stage. Maximum use of blowdown will minimize startup times.

During startup, any chemical excursions must be dealt with quickly and effectively. Increases in feedwater sodium and cation conductivity may indicate contamination from the makeup system, contamination from inspection, cleaning and maintenance activities or condenser leakage. The source must be found and the problem corrected at once. Excursions affecting (lowering) evaporator circuit water pH may be corrected immediately by feeding trisodium phosphate or 1-2 ppm of sodium hydroxide providing water from this circuit is not used for steam attemperation or as feedwater to a higher pressure circuit. If such treatment becomes necessary, avoid dryout conditions in the evaporators and excess carryover of evaporator water impurities into the steam.

Effects of cycle contamination are magnified at startup due to relatively low flow rates for condensate, feedwater and steam. Cation conductivity may increase as a result of air ingress due to either aeration of water during the shutdown period or air in-leakage during startup. Shutdown and layup protection procedures conducted in accordance with the guiding principles of Section 2.3 will minimize these effects during ensuing startups. The change to evaporator circuit water chemistry will be minimal compared to contamination involving the makeup system, chemical cleaning activities, condensate polishers or condenser leaks.

Step 5 – Full Load

Full load can be achieved when chemical limits are within the HRSG Cycle Chemistry Guidelines for drum type evaporator circuits operating on AVT[(2)].

5.4 Startup of Units with All-Volatile Treatment (AVT) of Once-Through HRSG Circuits

Only a limited number of HRSGs include once-through evaporator circuits; in many cases, the feedwater to this circuit is provided by a low pressure evaporator. The feedwater system typically does not include provision for circulation and cleanup. The design includes a condensate polisher or filter in some but not all cases. The once-through evaporator may include a separator that can be used to remove impurities present in wet steam during the startup period. Operating startup procedures will reflect the capabilities and requirements of the specific design.

During off-load conditions, deposited impurities may have been released into the circuit or have entered from outside, e.g. condenser leaks, CO_2 with air in-leakage. Therefore, it is important to consider the effects on the feedwater and steam cation conductivity, silica, sodium, chloride and sulfate concentrations during startup. Oxygen concentrations in the feedwater also require special consideration. Restrictions will need to be applied to these parameters, but some relaxation from the normal HRSG Cycle Chemistry Guideline values[(2)] should be possible until steady state operating conditions are achieved.

Depending on the plant, and the shutdown and layup conditions adopted, several steps will be required for startup (in addition to filling the HRSG following a long shutdown and safely venting the nitrogen, if used). The steps used during startup will be plant specific and, depending on the practicality, the following stages should be monitored carefully, at least during a trial period:

- Feedwater to HRSG, with emphasis on purity and ammonia dosing control
- Pressure raising in HRSG, with emphasis on feedwater purity and ammonia dosing control
- Steam from HRSG circuits and feedwater purity
- Steam to turbine and feedwater purity
- Load raising, with emphasis on attaining limits for full load operation

At full load, the normal HRSG Cycle Chemical Guidelines values[(2)] should be achieved. There may be room for relaxation, particularly, as regards silica in steam, during startup, the earlier stages of operation and during low load operation, provided the parameters are within the HRSG Cycle Chemistry Action Levels 1-3. (Note that the guidelines are the same for all operating pressures for once-through evaporators.) The core parameters, sodium, cation conductivity and oxygen, should be monitored in the condensate, feedwater, and steam, and also pH, silica and iron, if possible, at least during a trial period. The normal operating levels, as given in the HRSG Cycle Chemistry Guidelines[(2)] should be achieved as soon as possible.

A road map showing a scheme for startup of a unit with once-through evaporator circuits operating with AVT is given in Figure 5-3. The time taken to achieve the required target values will be plant dependent. This should be determined for each unit, used as guidance for subsequent startups, and amended in the light of operating experience. The procedure can usually be curtailed for warm and hot starts.

The road map for startup of once-through HRSG units operating on AVT, Figure 5-3, can be divided into five steps.

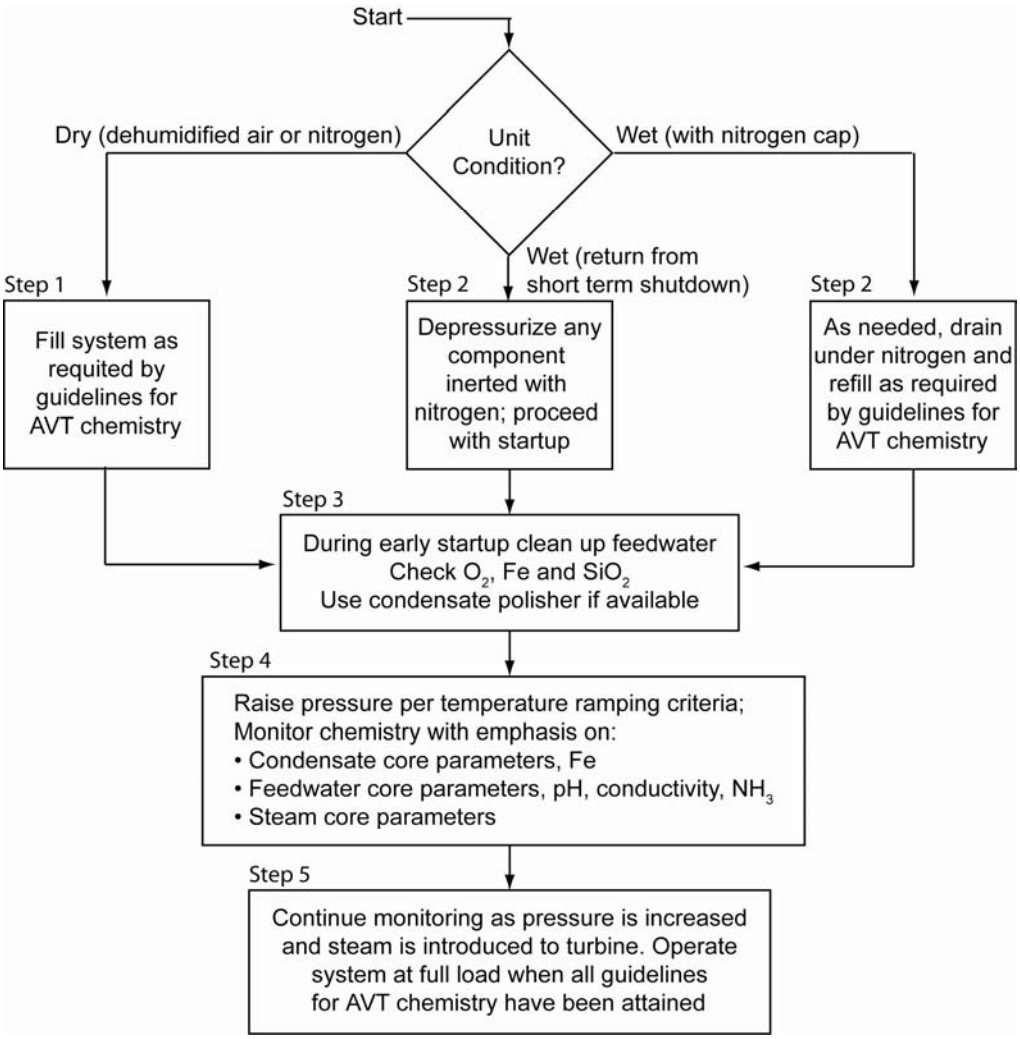


Figure 5-3
Road Map for Startup of Combined Cycle Units with Once-Through Evaporator HRSG Circuits Treated All Volatile Treatment (AVT) Chemistry

The steps are essentially similar to those described for HRSGs with AVT drum circuits, except that for once-through evaporator circuits, control of evaporator water purity can not be achieved by blowdown, and, the absence of the "reservoir" of the drum and steam separation devices in once-through designs, means that the acceptable level of impurities is much less than for drum circuits.

Step 1 – System Stored Dry (Dehumidified Air or Nitrogen)

If the system has been stored dry (Section 3.2), it should be filled with deaerated water which meets the HRSG Cycle Chemistry Guidelines for once-through evaporator circuits operating on AVT[(2)].

Step 2 – System Stored Wet

If the system has been stored wet with a surplus of ammonia and a nitrogen cap as indicated in Section 3.2, it must be drained under nitrogen and refilled with deaerated water meeting the HRSG Cycle Chemistry Guidelines for once-through units operating on AVT[(2)].

If the system is returning to service from a short term shutdown without changing the chemistry and has been protected as indicated in Section 3.2, it is allowable to proceed with startup of the cycle.

Step 3 – Feedwater Conditions

The following limits for the HRSG feedwater are required prior to raising pressure in the HRSG:

- Oxygen <100 ppb
- Iron <30 ppb
- Silica <30 ppb

During startup following major maintenance, the levels of corrosion products (iron) can be very high initially, especially if the unit has an air cooled condenser. Silica may also be a problem, particularly after maintenance activity. It is also useful to monitor these conditions in the condensate.

Feedwater dosing should be practiced as needed to meet control limits for ammonia.

Feedwater cleanup is possible in units equipped with condensate polishing. When these limits are attained, raising pressure in the HRSG evaporator circuits can begin consistent with limits for AVT chemistry and equipment requirements for temperature ramping. Good control of feedwater in the early startup will require close compliance with the guidelines for unit shutdown and layup.

Step 4 – Monitoring

After firing the HRSG, monitoring must be fully implemented, both for chemistry parameters, and to ensure that temperature ramps are maintained according to the equipment manufacturer's specifications.

During startup, any chemical excursions must be dealt with quickly and effectively. Increases in feedwater sodium and cation conductivity may indicate contamination from the makeup system, contamination from inspection, cleaning and maintenance activities, condensate polisher malfunction or condenser leakage. The source must be found and the problem corrected at once.

Effects of cycle contamination are magnified at startup due to relatively low flow rates for condensate, feedwater and steam. Cation conductivity may increase as a result of air ingress due to either aeration of water during the shutdown period or air in-leakage during startup. Shutdown

and layup protection procedures conducted in accordance with the guiding principles of Section 2.3 will minimize these effects during ensuing startups.

Step 5 – Full Load

Full load can be achieved when chemical limits are within the HRSG Cycle Chemistry Guidelines for once-through circuits operating on AVT[(2)].

5.5 Caustic Treatment

For cold starts, the ramp to full pressure is dependent on the HRSG/turbine design and stress limitations. Analysis of the evaporator water suspended solids gives a measure of the magnetite inventory and the source of evaporator circuit tube deposits. In order to give protection against contaminant ingress during the initial stages of operation, the concentration of sodium hydroxide should be maintained within the limits specified in the HRSG Cycle Chemistry Guidelines[(2)]. Heavy blowdown can be maintained throughout the startup until contamination levels are well within the specified limits. Care should be taken to avoid excessive sodium hydroxide concentrations in the evaporator water and carryover of impurities into the steam.

For hot starts, avoid making changes to the HRSG evaporator chemistry and maintain conditions within the specifications. Avoid dryout in the evaporators and excessive carryover of impurities into the steam.

Guidance on caustic treatment (CT) for drum type evaporators circuits is given in the HRSG Cycle Chemistry Guidelines[(2)].

The basic considerations outlined for startup of units with drum circuits operating on AVT, also apply to those treated with CT, with the addition that special care has to be taken to prevent any carryover of sodium hydroxide in the evaporator water, as this could lead to stress corrosion of austenitic components in the steam circuit. The importance of avoiding the presence of sodium hydroxide in plants with evaporators that suffer dryout conditions or carryover of evaporator water into steam can not be stressed too strongly.

During startups, the initial lower drum pressure permits evaporator water chemical concentrations to be higher than those at normal unit operating pressures. Also, the cumulative operating hours per year for which the various action levels can be exceeded are twice the values for cycling units, as compared to base loaded units.

As mentioned previously, special care has to be taken to avoid excessively high concentrations of sodium hydroxide in the evaporator water, and carryover of sodium hydroxide into the steam. This can be prevented by carefully monitoring sodium in steam. The steps used during startup will be plant specific and, depending on the practicality, the following stages should be monitored, at least during a trial period:

- Feedwater to HRSG, with emphasis on purity and ammonia dosing control
- Pressure raising in HRSG, with emphasis on chemistry control in drum evaporator circuits

- Steam from HRSG circuit, with emphasis on carryover, steam purity and feedwater purity
- Steam to turbine, with emphasis on carryover, steam purity and feedwater purity
- Load raising, with emphasis on attaining limits for full load operation

At full load, the normal values given in the HRSG Cycle Chemistry Guidelines[2] should be achieved. There may be room for relaxation, particularly, as regards silica in steam, during startup and the earlier stages of operation and during low load operation, provided the parameters are within the HRSG Cycle Chemistry action levels 1-3. The core parameters, sodium, cation conductivity and oxygen, should be monitored in condensate, feedwater, evaporator water (preferably at downcomer), including pH and specific conductivity or sodium hydroxide concentration, and steam. The normal operating levels, as given in the HRSG Cycle Chemistry Guidelines[2] should be achieved as soon as possible.

A road map for startup of units with drum type evaporator circuits operating with CT is given in Figure 5-4. The time taken to achieve the required target values will be plant dependent. This should be determined for each unit, used as guidance for subsequent startups, and amended in the light of operating experience. The procedure can normally be curtailed for warm and hot starts.

The road map for startup of drum units operating on CT, Figure 5-4, can be divided into five steps.

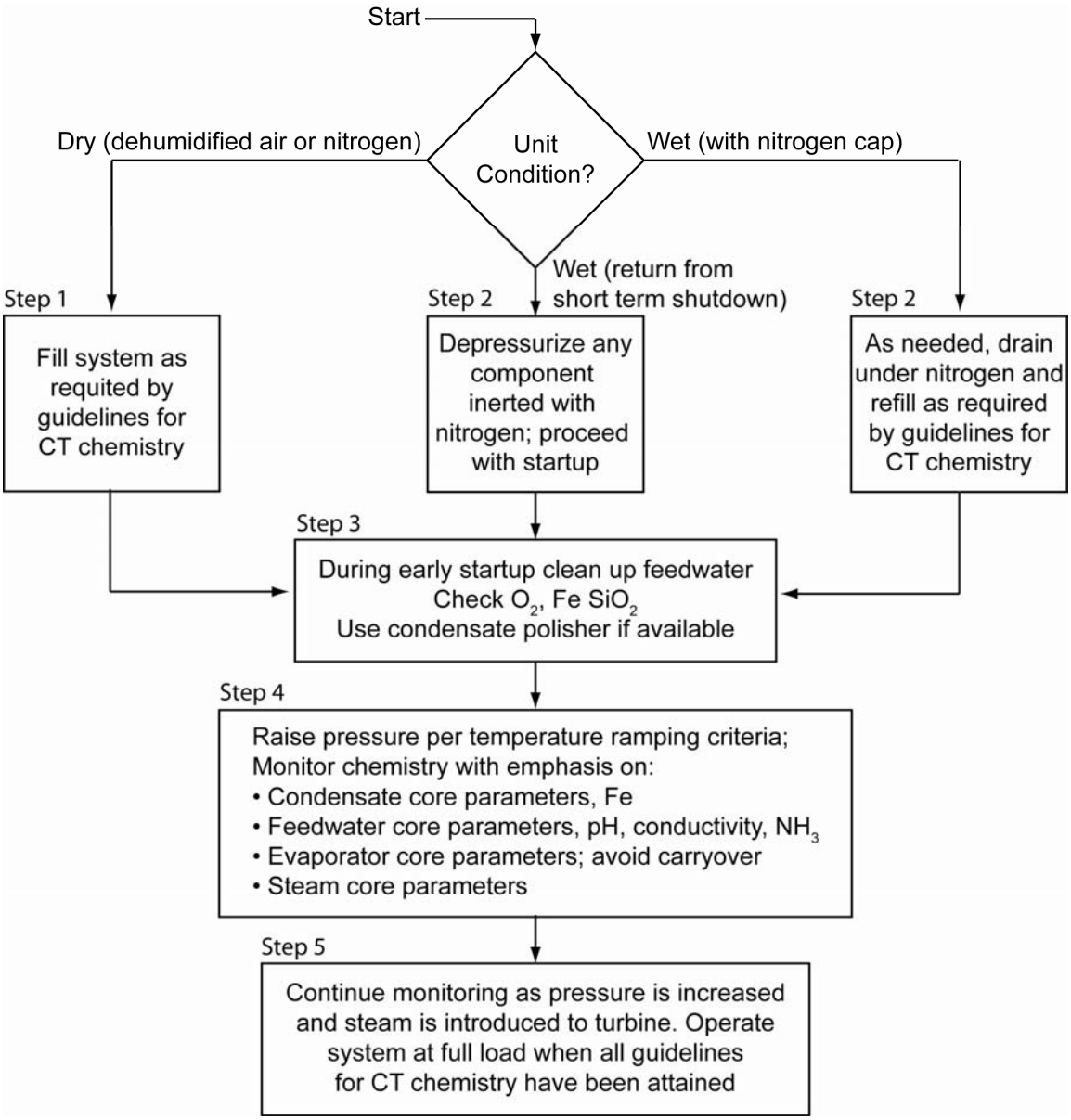


Figure 5-4
Road Map for Startup of Combined Cycle Units with Drum Type Evaporator HRSG Circuits Treated With Caustic Treatment (CT) Chemistry

The steps described in Figure 5-4 are essentially similar to those for drum evaporator circuits on AVT. Again it should be noted that additional care is required to avoid excessive carryover of evaporator water impurities and conditioning chemicals (sodium hydroxide) into the steam.

Step 1 – System Stored Dry (Dehumidified Air or Nitrogen)

If the system has been stored dry (Section 3.2), it should be filled with deaerated water which meets the HRSG Cycle Chemistry Guidelines for drum evaporator circuits operating on CT[(2)].

Step 2 – System Stored Wet

If the system has been stored wet with a surplus of ammonia and a nitrogen cap as indicated in Section 3.2, it must be drained under nitrogen and refilled with deaerated water meeting the HRSG Cycle Chemistry Guidelines for drum evaporator circuits operating on CT[(2)].

If the system is returning to service from a short term shutdown without changing the chemistry and has been protected as indicated in Section 3.2, it is allowable to proceed with startup of the cycle.

Step 3 – Feedwater Conditions

The following limits for the feedwater are required prior to raising pressure in the HRSG:

- Oxygen <100 ppb
- Iron <100 ppb
- Silica <50 ppb

During startup following major maintenance, the levels of corrosion products (iron) can be very high initially, especially if the unit has an air cooled condenser. Silica may also be a problem, particularly after maintenance activity. It is also useful to monitor these conditions in the condensate.

Feedwater dosing should be practiced as needed to meet control limits for ammonia.

When these limits are attained, raising pressure in the HRSG evaporator circuits can begin consistent with limits for CT chemistry and equipment requirements for temperature ramping. Good control of feedwater in the early startup will require close compliance with the guidelines for unit shutdown and layup.

Step 4 – Monitoring

After firing the HRSG, monitoring must be fully implemented, both for chemistry parameters, and to ensure that temperature ramps are maintained according to the equipment manufacturer's specifications.

During startup, the concentration vs. pressure curves given in the HRSG Cycle Chemistry Guidelines[(2)] can be utilized to control conductivity, sodium, silica, chloride and sulfate. Evaporator pressure should remain at reduced levels such that these limits are maintained before pressure can be increased to the next stage. Maximum use of blowdown and condensate polishing (if available) will minimize startup times.

During startup, any chemical excursions must be dealt with quickly and effectively. Increases in feedwater sodium and cation conductivity may indicate contamination from the makeup system, contamination from inspection, cleaning and maintenance activities, condensate polisher malfunction or condenser leakage. The source must be found and the problem corrected at once.

Excursions affecting (lowering) the evaporator pH must be corrected immediately by feeding 1-2 ppm of sodium hydroxide to the evaporator water. Match the sodium hydroxide to the chloride concentration. Do not over-feed sodium hydroxide. Avoid dryout in the evaporators and excess carryover of evaporator water impurities and treatment chemicals into the steam.

Effects of cycle contamination are magnified at startup due to relatively low flow rates for condensate, feedwater and steam. Cation conductivity may increase as a result of air ingress due to either aeration of water during the shutdown period or air in-leakage during startup. Shutdown and layup protection procedures conducted in accordance with the guiding principles of Section 2.3 will minimize these effects during ensuing startups. The change to evaporator circuit water chemistry will be minimal compared to contamination involving the makeup system, chemical cleaning activities, condensate polishers or condenser.

Step 5 – Full Load

Full load can be achieved when chemical limits are within the HRSG Cycle Chemistry Guidelines for drum units operating on CT[(2)].

5.6 Startup of Units with Oxygenated Treatment (OT) of Drum HRSG Circuits

A relatively quick startup after both short term and intermediate term layup is an important advantage of OT. Usually, due to air ingress during layup, the feedwater and HRSG evaporator water pH may be reduced. Increased ammonia dosing is required until the feedwater and HRSG evaporator circuit water pH is stabilized in the normal target value range. Dosing with hydrazine or other reducing agents is not allowed or required.

Startup is accomplished using essentially the same startup procedure as used for units with drum circuits on AVT, as discussed in Section 5.3 and summarized in the Figure 5-2 road map. This road map consists of five steps, resulting in normal operation of the unit on AVT. Because combined cycle units start up and raise load so quickly, oxygen dosing and other chemistry changes (reduction of pH in the feedwater and evaporator water) that may be needed to operate with OT chemistry should not be made until startup under AVT conditions is complete. Effective venting of external deaerator and heaters (if such devices are part of the design) during the startup and closure of these vents prior to oxygen dosing is also very important. Oxygen dosing of the feedwater cannot be resumed until specific chemistry criteria are attained in the feedwater and the evaporator water of drum evaporator circuits.

For startups following short term layup, there should be no holds or other ramping activities, if the OT is operated in the optimum fashion according to the HRSG Cycle Chemistry Guidelines[(2)]. Also, there is normally no need for pH reduction as the pH need not be increased prior to the shutdown, as discussed in Section 4.6. For startups following longer duration shutdowns, the feedwater iron levels still should not be a critical parameter. Here the main monitoring parameters are economizer inlet cation conductivity, oxygen, and pH (by means of specific conductivity) as well as evaporator water cation conductivity, oxygen, and pH.

Depending on the plant, and the shutdown and layup conditions adopted, several steps will be required for startup (in addition to filling the HRSG following a long shutdown and safely venting the nitrogen, if used). The steps used during startup will be plant specific and, depending on the practicality, the following stages should be monitored carefully, at least during a trial period:

- Feedwater to HRSG, with emphasis on purity and ammonia dosing control
- Pressure raising in HRSG, with emphasis on chemistry control in drum evaporator circuits
- Steam from HRSG circuit, with emphasis on carryover, steam purity and feedwater purity
- Steam to turbine, with emphasis on carryover, steam purity and feedwater purity
- Load raising, with emphasis on attaining limits for full load operation

During startups, the initial lower drum pressure permits evaporator water chemical concentrations to be higher than those at normal unit operating pressures. Also, the cumulative operating hours per year for which the various action levels can be exceeded are twice the values for cycling units, as compared to base loaded units.

Figure 5-5 shows a road map for startup of drum units operating with OT. The first five steps are those followed to accomplish startup on AVT. Thesixth step of the road map covers conversion from AVT to OT, which should only be done after a successful startup has been completed and all requisite conditions have been met.

Step 1 – System Stored Dry (Dehumidified Air or Nitrogen)

If the system has been stored dry (Section 3.2), it should be filled with deaerated water which meets the HRSG Cycle Chemistry Guidelines for drum type evaporator circuits operating on AVT[(2)].

Step 2 – System Stored Wet

If the system has been stored wet with a surplus of ammonia and a nitrogen cap as indicated in Section 3.2, it must be drained under nitrogen and refilled with deaerated water meeting the HRSG Cycle Chemistry Guidelines for drum type evaporator circuits operating on AVT[(2)].

If the system is returning to service from a short term shutdown without changing the chemistry and has been protected as indicated in Section 3.2, it is allowable to proceed with startup of the cycle.

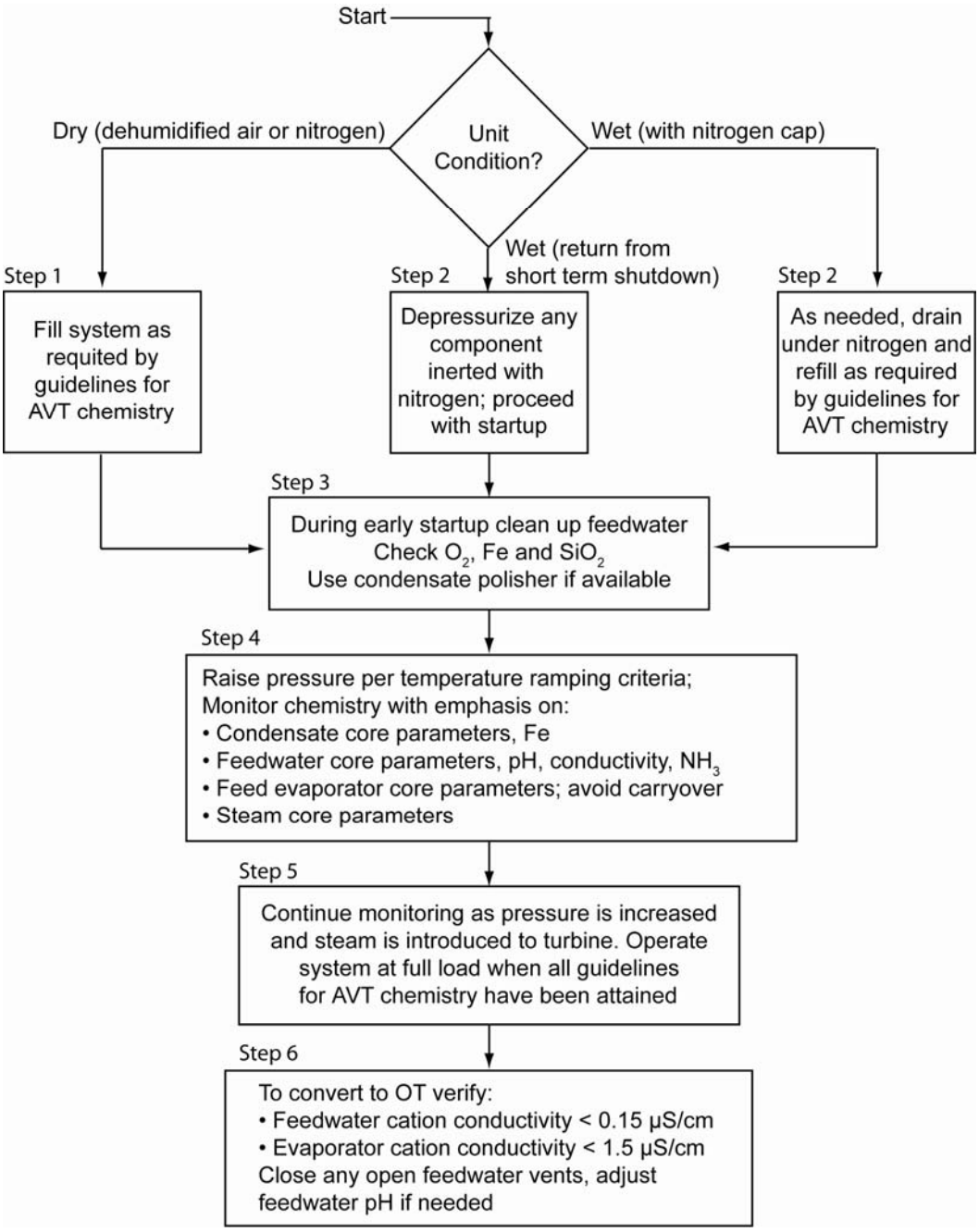


Figure 5-5
Road Map for Startup and OT Conversion of Combined Cycle Units with Drum Type Evaporator HRSG Circuits Treated With Oxygenated Treatment (OT) Chemistry

Step 3 – Feedwater Conditions

The following limits for the feedwater are required prior to raising pressure in the HRSG:

- Oxygen <100 ppb
- Iron <100 ppb
- Silica <50 ppb

During startup following major maintenance, the levels of corrosion products (iron) can be very high initially, especially if the unit has an air cooled condenser. Silica may also be a problem, particularly after maintenance activity. It is also useful to monitor these conditions in the condensate.

Feedwater dosing should be practiced as needed to meet control limits for ammonia.

Feedwater cleanup is possible in units equipped with condensate polishing. When these limits are attained, raising pressure in the HRSG evaporator circuits can begin consistent with limits for OT chemistry following short term shutdowns or AVT following longer shutdowns and equipment requirements for temperature ramping. Good control of feedwater in the early startup will require close compliance with the guidelines for unit shutdown and layup.

Step 4 – Monitoring

After firing the HRSG, monitoring must be fully implemented, both for chemistry parameters, and to ensure that temperature ramps are maintained according to the equipment manufacturer's specifications. External deaerators and feedwater heaters, if included in the design should be vented thoroughly at this time.

During startup, the concentration vs. pressure curves given in the HRSG Cycle Chemistry Guidelines[(2)] can be utilized to control conductivity, sodium, silica, chloride and sulfate. Evaporator pressure should remain at reduced levels such that these limits are maintained before pressure can be increased to the next stage. Maximum use of blowdown will minimize startup times.

During startup, any chemical excursions must be dealt with quickly and effectively. Increases in feedwater sodium and cation conductivity may indicate contamination from the makeup system, contamination from inspection, cleaning and maintenance activities or condenser leakage. The source must be found and the problem corrected at once. Excursions affecting (lowering) evaporator circuit water pH may be corrected immediately by feeding trisodium phosphate or 1-2 ppm of sodium hydroxide providing water from this circuit is not used for steam attemperation or as feedwater to a higher pressure circuit. If such treatment becomes necessary, avoid dryout conditions in the evaporators and excess carryover of evaporator water impurities into the steam.

Effects of cycle contamination are magnified at startup due to relatively low flow rates for condensate, feedwater and steam. Cation conductivity may increase as a result of air ingress due to either aeration of water during the shutdown period or air in-leakage during startup. Shutdown

and layup protection procedures conducted in accordance with the guiding principles of Section 2.3 will minimize these effects during ensuing startups. The change to evaporator circuit water chemistry will be minimal compared to contamination involving the makeup system, chemical cleaning activities, condensate polishers or condenser leaks.

Step 5 – Operation on AVT

Completion of load raising and normal operation can be achieved when chemical limits are within the HRSG Cycle Chemistry Guidelines for drum type evaporator circuits operating on AVT[(2)]. For startup after short term shutdowns, the feedwater and evaporator pH may be at levels acceptable for OT operation.

Step 6 - Transition to OT

This step, covering conversion of the treatment from AVT to OT should not begin until startup on AVT has been completed and unit operation is stable. In addition, certain cycle purity requirements for OT operation must be attained.

A measured feedwater cation conductivity of <0.15 µS/cm is the first precondition for the transition to OT. Deaerator (if furnished) and heater vents (if furnished) should then be closed for steady state operation with OT.

A measured evaporator water cation conductivity of <1.5 µS/cm is the second precondition for the transition to OT. In case of need, the blowdown is used to reduce the evaporator water cation conductivity.

If the above conditions are not satisfied, the unit has to continue operation with AVT.

Upon initiation of oxygen dosing, dissolved oxygen levels should be monitored at the economizer inlet and evaporator downcomer sample points. The permissible feedwater oxygen dose is dependent on the oxygen recirculation ratio (economizer inlet oxygen to downcomer oxygen); overfeed of oxygen will result in high levels of oxygen in the downcomer. Also, the pH of the feedwater and evaporator may be reduced if above the levels required for OT operation as may be needed when returning from long outages. Any external deaerator (if furnished) and heater vents (if furnished) should then be closed after assuring these vessels have been effectively vented as required in Step 4.

With oxygen dosing, the chemistry is controlled according to the cycle chemistry guidelines for OT.[(2)]

5.7 Startup of Units with Oxygenated Treatment (OT) of Once-Through HRSG Circuits

Only a limited number of HRSGs include once-through evaporator circuits; in many cases, the feedwater to this circuit is provided by a low pressure evaporator. The feedwater system typically does not include provision for circulation and cleanup. The design includes a

condensate polisher or filter in some but not all cases. The once-through evaporator may include a separator that can be used to remove impurities present in wet steam during the startup period. Operating startup procedures will reflect the capabilities and requirements of the specific design. Dosing with hydrazine or other reducing agents is not allowed or required.

Startup is accomplished using essentially the same startup procedure as used for units with once-through evaporator circuits on AVT, as discussed in Section 5.4 and summarized in the Figure 5-3 road map. This road map consists of five steps, resulting in normal operation of the unit on AVT. Conversion to OT chemistry should not be initiated until startup under AVT conditions is complete and the feedwater confirmed to be of satisfactory purity. Effective venting of external deaerator and heaters (if such devices are part of the design) during the startup and closure of these vents prior to oxygen dosing is also very important. Oxygen dosing of the feedwater cannot be resumed until specific chemistry criteria are attained in the feedwater.

Depending on the plant, and the shutdown and layup conditions adopted, several steps will be required for startup (in addition to filling the HRSG following a long shutdown and safely venting the nitrogen, if used). The steps used during startup will be plant specific and, depending on the practicality, the following stages should be monitored carefully, at least during a trial period:

- Feedwater to HRSG, with emphasis on purity and ammonia dosing control
- Pressure raising in HRSG, with emphasis on feedwater purity and ammonia dosing control
- Steam from HRSG circuit and feedwater purity
- Steam to turbine and feedwater purity
- Load raising, with emphasis on attaining limits for full load operation

For startups following short term layup, there should be no holds or other ramping activities, if the OT is operated in the optimum fashion according to the HRSG Cycle Chemistry Guidelines[2]. Also, there is normally no need for pH reduction as the pH need not be increased prior to the shutdown, as discussed in Section 4.7. For startups following longer duration shutdowns, the feedwater iron levels still should not be a critical parameter. Here the main monitoring parameters are economizer inlet cation conductivity, oxygen, and pH (by means of specific conductivity).

Figure 5-6 shows a road map for startup of drum units operating with OT. The first five steps are those followed to accomplish startup on AVT. The sixth step of the road map covers conversion from AVT to OT, which should only be done after a successful startup has been completed and the requisite feedwater purity requirement has been met.

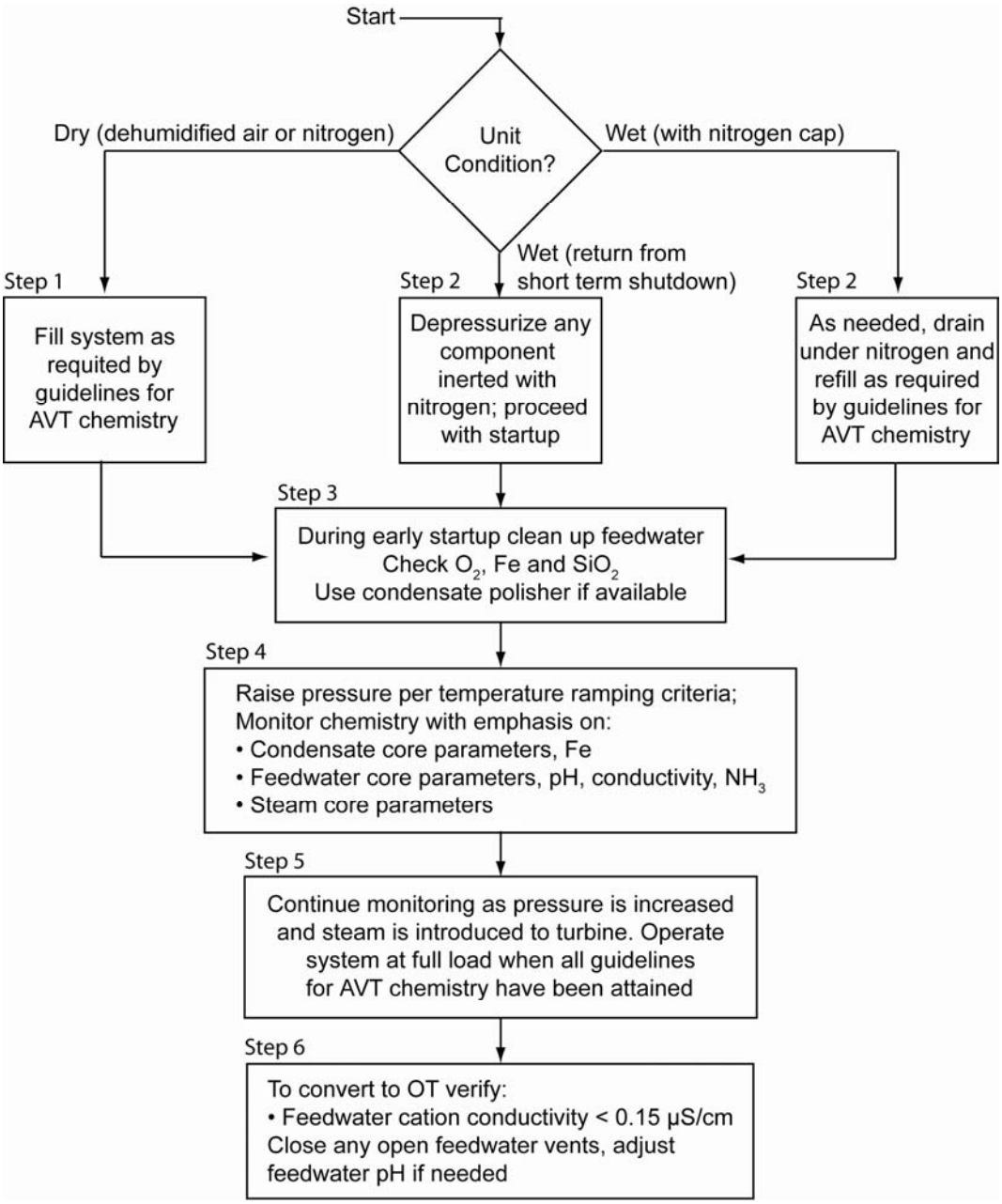


Figure 5-6
Road Map for Startup of Combined Cycle Units with Once-through Evaporator HRSG Circuits Treated with Oxygenated Treatment (OT) Chemistry

Step 1 – System Stored Dry (Dehumidified Air or Nitrogen)

If the system has been stored dry (Section 3.2), it should be filled with deaerated water which meets the HRSG Cycle Chemistry Guidelines for once-through evaporator circuits operating on AVT[(2)].

Step 2 – System Stored Wet

If the system has been stored wet with a surplus of ammonia and a nitrogen cap as indicated in Section 3.2, it must be drained under nitrogen and refilled with deaerated water meeting the HRSG Cycle Chemistry Guidelines for once-through evaporator circuits operating on AVT[(2)].

If the system is returning to service from a short term shutdown without changing the chemistry and has been protected as indicated in Section 3.2, it is allowable to proceed with startup of the cycle.

Step 3 – Feedwater Conditions

The following limits for the feedwater are required prior to raising pressure in the HRSG:

- Oxygen <100 ppb
- Iron <30 ppb
- Silica <30 ppb

During startup following major maintenance, the levels of corrosion products (iron) can be very high initially, especially if the unit has an air cooled condenser. Silica may also be a problem, particularly after maintenance activity. It is also useful to monitor these conditions in the condensate.

Feedwater dosing should be practiced as needed to meet control limits for ammonia.

Feedwater cleanup is possible in units equipped with condensate polishing. When these limits are attained, raising pressure in the HRSG evaporator circuits can begin consistent with limits for OT following short term shutdowns or AVT following longer shutdowns and the equipment requirements for temperature ramping. Good control of feedwater in the early startup will require close compliance with the guidelines for unit shutdown and layup.

Step 4 – Monitoring

After firing the HRSG, monitoring must be fully implemented, both for chemistry parameters, and to ensure that temperature ramps are maintained according to the equipment manufacturer's specifications. External deaerators and feedwater heaters, if included in the design should be vented thoroughly at this time.

During startup, any chemical excursions must be dealt with quickly and effectively. Increases in feedwater sodium and cation conductivity may indicate contamination from the makeup system, contamination from inspection, cleaning and maintenance activities or condenser leakage. The source must be found and the problem corrected at once.

Effects of cycle contamination are magnified at startup due to relatively low flow rates for condensate, feedwater and steam. Cation conductivity may increase as a result of air ingress due to either aeration of water during the shutdown period or air in-leakage during startup. Shutdown

and layup protection procedures conducted in accordance with the guiding principles of Section 2.3 will minimize these effects during ensuing startups. The change to evaporator circuit water chemistry will be minimal compared to contamination involving the makeup system, chemical cleaning activities, condensate polishers or condenser leaks.

Step 5 – Operation on AVT

Completion of load raising and normal operation can be achieved when chemical limits are within the HRSG Cycle Chemistry Guidelines for once-through evaporator circuits operating on AVT[(2)]. For startup after short term shutdowns, the feedwater pH may be at levels acceptable for OT operation.

Step 6 - Transition to OT

This step, covering conversion of the treatment from AVT to OT should not begin until startup on AVT has been completed and unit operation is stable. In addition, a measured feedwater cation conductivity of <0.15 µS/cm should be attained before initiating the transition to OT.Until this requirement is satisfied, the unit has to continue operation with AVT.

Only when the above mentioned precondition is fulfilled (feedwater cation conductivity < 0.15 µS/cm), is oxygenated dosing permitted. Also, the pH of the feedwater and evaporator may be reduced if above the levels required for OT operation as may exist when returning from long outages. Any external deaerator (if furnished) and heater vents (if furnished) should then be closed after assuring these vessels have been effectively vented as required in Step 4.

With oxygen dosing, the chemistry is controlled according to the cycle chemistry guidelines for OT.[(2)]

5.8 References

1. Delivering High Reliability Heat Recovery Steam Generators. EPRI, Palo Alto, CA: March 2003.1004240.
2. Cycle Chemistry Guidelines for Combined Cycle/Heat Recovery Steam Generators (HRSGs). EPRI, Palo Alto, CA: 2006. 1010438.
3. G. M. W. Mann and R. Garnsey, “Waterside Corrosion Associated with Two-Shift Boiler Operation on All-Volatile Treatment Chemistry", Corrosion 79 Conference, *Materials Performance*, October 1980, pp. 32-38.

A EQUIPMENT PROTECTION VIA ESTABLISHMENT OF BARRIER FILMS

As discussed earlier in these guidelines, the most widely used and effective approaches to equipment protection normally involve wet and dry layup.

Two general types of treatment have been used for equipment protection by establishment of a barrier between the oxide surface and any water or moisture that may be present. Included here are the so-called vapor phase inhibitor (VPI) treatments and certain amines, specifically filming amines; included here are filming amine-neutralizing amine blends, also known as polyamines.

Use of these treatments would appear to meet many of the guiding principles of equipment protection (Section 2.3) in ways that could be simpler and more cost effective than the traditional wet and dry layup methods. However, the properties of the chemicals used are not fully understood and experience with their use for equipment protection in operating plants is limited or appears impractical. Also, questions exist with respect to possible effects of the chemicals used to establish barriers on unit operation. Further research would be needed to improve the understanding of the materials with respect to their suitability for routine use in protection of steam and water touched surfaces of combined cycle units.

These protection approaches are briefly reviewed in the following subsections but are not considered further in these guidelines.

A.1 Vapor Phase Inhibitors

VPI treatments encompass a wide range of products for a multitude of equipment and product protection applications.[1, 2] They have been used for extended storage of HRSGs.[3]

The materials used to protect steam and water touched surfaces of power plant systems are typically characterized as carboxylic acid salts. The corresponding cations are typically amines, thus providing a film of material composed of hydrophilic sites adjacent to the surface to be protected and hydrophobic sites adjacent to the environment.

VPIs used for this application are typically provided in crystalline form and may be added to the component to be protected manually, though spraying is generally practiced to enhance distribution of the material. Though typically applied to the surface to be protected while dry they will also provide protection if dissolved in water. The dry crystals undergo sublimation at ambient temperatures and may be used to protect wet and dry surfaces as well as the liquid-vapor interface. Due to their volatile nature, components to be protected must be sealed thoroughly following addition of the VPI.

VPIs are available from several manufacturers and suppliers. If the inhibitor is properly applied, components can reportedly be protected for several months and up to two years, depending on the local environment and effectiveness of sealing measures. Protection effectiveness can be assessed by inspection or by use of corrosion coupons of the materials of the component to be protected.

VPIs used in components such as HRSGs reportedly do not need to be removed from surfaces before the unit is placed in service. The inhibitors are subject to thermal decomposition at low temperatures forming volatile compounds which can be removed from the cycle via the vents at low pressure. Effects of such practice on cycle chemistry during startup are indicated to be insubstantial though there have been no definitive studies of startup chemistry in high pressure fossil units.

VPIs are typically and successfully used for other purposes, such as protection of new or replacement components such as steam generator tubing assemblies, and extended protection (mothballing) of equipment. Use of VPIs for short term and long term protection of operational HRSG components would appear to be both time consuming and cost prohibitive. They could be effectively applied in combined cycle units where extended protection of the HRSG or other components is required.

A.2 Filming Amines and Polyamines

Filming amines, including the so-called polyamines (high molecular weight filming amines typically bended with neutralizing amines) have been advocated as a means of equipment protection under both operational and idle conditions.[4] With respect to equipment protection during shutdowns, claims have been made that these products can effectively protect surfaces of equipment that must be drained and opened for inspection. However, the nature of these products has not been investigated substantially and some concerns exist over their use in high pressure cycles. These concerns include:

- Possible thermal breakdown in the steam generator
- Effects of treatment overfeed, underfeed or loss of feed on equipment protection, corrosion product transport, and deposition
- Interactions with other treatment chemicals
- Transient or permanent fouling of condensate polisher or filter media

These concerns are potentially significant, as are their possible benefits, which appear to extend beyond equipment protection. For instance, use of octadecylamine for the purpose of improving steam turbine performance was evaluated in a steam turbine at a Russian research facility and shown to be significant.[5] However, prior attempts to use this treatment in fossil plants caused operating problems and as a consequence of this negative experience interest in these treatments was very limited until recent years when the polyamine formulations were introduced. Polyamine products are now in use in a variety of steam and power generation facilities around the world; however there are still many questions concerning their use that need to be answered. Given the fact that a better understanding of these treatments could offer the possibility of an

easy to implement, effective and inexpensive means of equipment protection during shutdowns, further investigation to understand the chemistry of filming amines could be a source of tremendous value to the cogeneration industry.

A.3 References

1. 1. B. A. Miksic, Use of Vapor Phase Corrosion Inhibitors (VCI's) for the Layup of Power Plant Equipment", *Proceedings: Fossil Plant Layup and Reactivation Conference*. EPRI, Palo Alto, CA: 1992. TR-101250.
2. 2 B. Miksic, R. Boyle, and B. Wuertz, "Efficacy of Vapor Phase Inhibitor Technology in Manufacturing", *Corrosion*, Vol. 6, No. 60, p. 515-522, NACE International, 2004.
3. 3. W.H. Stroman, S. Maudlin, and D. B. DeWitt-Dick, "HRSG Storage using Vapor Phase Inhibitor", presented at the ASME Research Committee on Power Plant and Environmental Chemistry, 2003 Spring Meeting, West Palm Beach, Florida, April 14-16, 2003.
4. 4. A. Bursik, P. Beezzoli, and A. Graf, "Cycle Chemistry in Cycles with Drum Boilers: Is there a Niche for the use of Alternative Organic Chemicals in the Continuum of Treatments?", *Proceedings: Seventh International Conference on Cycle Chemistry in Fossil Plants: June 3-5, 2003, Houston, Texas.* EPRI, Palo Alto, CA: 2004. 1009194.
5. 5. Turbine Steam Chemistry and Corrosion: Electrochemistry in LP Turbines, EPRI, Palo Alto, CA: 2001. 1006283.

B
OXYGEN REMOVAL TECHNIQUES FOR CYCLE MAKEUP WATER

The Guiding Principles of Section 2.3 clearly indicate the importance of maintaining strict control to prevent dissolved oxygen and carbon dioxide from entering the heat cycle in order to minimize corrosion and oxide transport. In contrast with this an EPRI survey conducted in 2000 determined that 44% of the responding organizations put aerated water directly into the cycle, while 77% put makeup into storage tanks which are vented to atmosphere.(1) A previous survey on cycle chemistry yielded comparable results.(2) These deficient design and operating philosophies on makeup water transfer are common in conventional fossil units and are unfortunately often applied in new combined cycle units. It is obvious that these types of operating procedures are counterproductive if corrosion is to be fully controlled.

This appendix describes methods by which makeup water can be deoxygenated (and some of these methods also remove carbon dioxide) and stored in such a way as to prevent further aeration.

Another important source of ingress of oxygen and carbon dioxide is air in-leakage via negative pressure in the condenser and low end of the heat cycle. This subject is addressed in Appendix C.

B.1 Vacuum Deaeration

Vacuum deaeration is a process, which removes both oxygen and carbon dioxide. A typical vacuum degasifier, which accomplishes this task, is shown in Figure B-1. This equipment consists of a packed tower with a vacuum pulled from beneath the packing and with water sprayed over the top of the packing. The water trickles down through the packing, which provides a large surface area for removal of oxygen and carbon dioxide. The vacuum induces vaporization of water and produces an upward flow of water vapor together with oxygen and carbon dioxide. The water is collected in the bottom of the tower and is pumped from there to the next stage of the system.

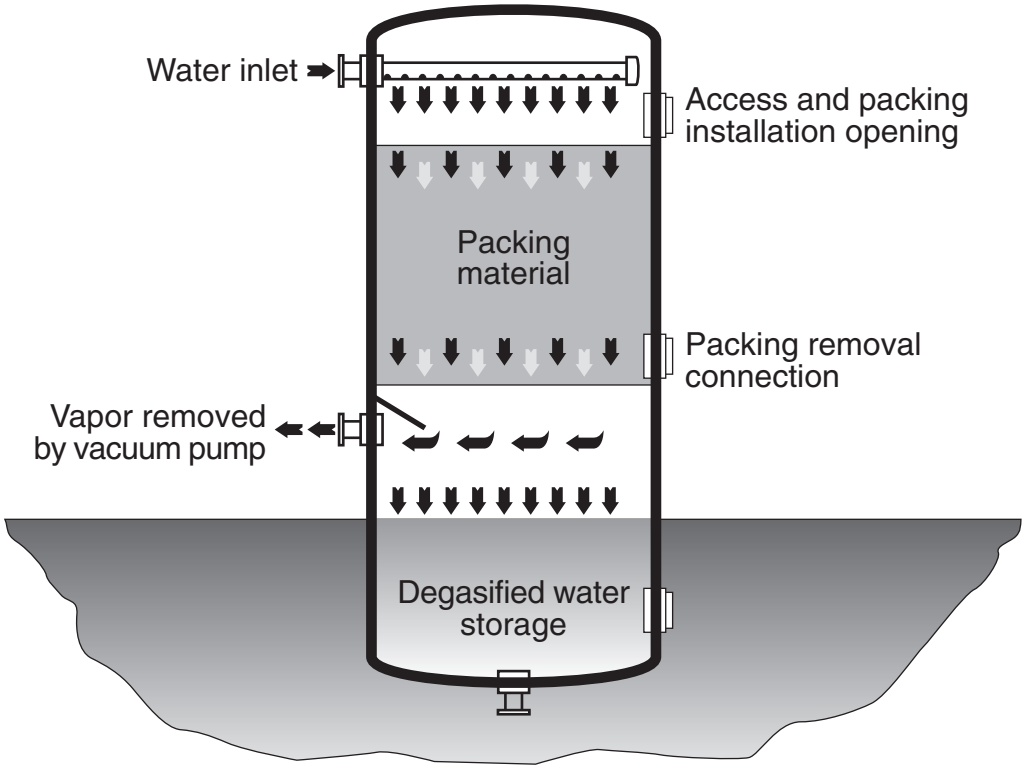


Figure B-1
Vacuum Degasifier

The process of vacuum degasification is based on Henry's Law, which states that the concentration of a gas in ideal (dilute) liquid solution is proportional to its vapor pressure (or partial pressure). Therefore, if the pressure over a solution is reduced by a vacuum, dissolved gases must leave the water and enter the vapor phase to establish a new equilibrium. Increasing the vacuum increases the degree of gas removal.

The vacuum supply to the degasifier can either be steam jet ejectors or vacuum pumps. The degasifier is typically located preceding the first anion unit of a demineralizer train in order to minimize the ionic loading to the anion unit by removing carbon dioxide. Forced draft decarbonators effectively remove carbon dioxide but saturate the water with oxygen.

Typical removal levels for a vacuum degasifier are: carbon dioxide to 5 ppb and oxygen to 10-20 ppb. Increasing the packing height in the tower and increasing vacuum will result in higher gas removal.

The vacuum degasifier is quite tall, typically in the range of 25-40 feet (7.6–12.2 m). One reason for this is to provide room for the packing material and the other is to provide sufficient suction head for the transfer pump. Because of its height, vacuum degasifiers may be difficult to backfit into an existing power plant arrangement. This equipment requires considerable maintenance in order to maintain constant vacuum conditions. In addition, the vacuum equipment is relatively energy intensive to operate.

For a typical 300 gpm (1130 L/m) vacuum degasifier unit, the following approximate costs in year 2005 US dollars, based on an earlier estimate[3], are as follows:

Capital Cost: $142,000.

Installation Cost: $73,500 to $226,000 depending on location and complexity of installation.

Operating and Maintenance (O&M) Cost: 3 to 5% of capital cost per year for normal operations.

B.2 Catalytic Oxygen Removal

The use of hydrazine or other reducing agents to remove oxygen is commonly practiced at many power plants and is usually fed at the condensate pump discharge or the outlet of the condensate polisher (if one is installed). The reaction between hydrazine and oxygen can be expressed as follows:

$$N_2H_4 + O_2 \rightarrow N_2 + 2H_2O \quad \textbf{(B-1)}$$

The reaction is stoichiometric, requiring equal amounts of hydrazine and oxygen for the reaction to proceed to completion. At ambient temperatures this reaction proceeds very slowly. However, in the presence of a catalyst, such as activated carbon, the reaction proceeds rapidly. Therefore, this technology can and is being used to remove oxygen from makeup water. The equipment consists of a vessel containing activated carbon to which hydrazine is fed using a positive displacement chemical pump. The process was patented [4] by a contract water treatment service provider and is said to achieve makeup oxygen concentrations less than 10 ppb.

Overall costs in UD dollars for the catalytic process are about $1.30 to $1.85 per 1000 gallons (approximately $0.34-$0.49/1000 L) depending on system flow rates.

This catalytic process can treat the water either going to storage or coming from storage. However, when large quantities of water are required, such as during startups, it may be impractical to provide equipment of sufficient size to meet such demands when processing water from storage.

One disadvantage of this catalytic process is that carbon dioxide is not removed. Therefore, when used in demineralizer systems treating waters high in bicarbonate alkalinity, operating costs can be expected to be substantially higher than when using a vacuum degasifier, for example. However, when the catalytic systems are used in conjunction with a membrane system, both carbon dioxide and oxygen can be simultaneously removed (see discussion which follows under membrane systems).

Another disadvantage associated with the carbon bed system is that an ion exchange bed is required to remove excess hydrazine and carbon leachables from the effluent stream.[4] Another possible concern relates to the use of hydrazine, a reducing agent. Extreme overfeed of hydrazine (or any alternative reducing agent applied for the purpose of catalytic oxygen removal from the makeup) could result in introduction of water with a negative (reducing) potential to units

operated under oxidizing conditions. Such action would violate the Guiding Principles of Section 2.3.

B.3 Gas Transfer Membrane Systems

Membrane systems are presently utilized today for many applications, including reverse osmosis, ultrafiltration, microfiltration, and electrodeionization. Another membrane process, which is achieving popularity in water treatment applications, is the use of gas transfer membrane (GTM) technology. Contract water treatment service providers now typically use this technology in favor of catalytic oxygen removal.

The membranes used for the removal of oxygen and carbon dioxide from makeup water are constructed of an array or bundle of hollow fiber hydrophobic polypropylene membranes which are gas permeable and water impermeable. The hollow fiber configuration, with the gas phase inside the fiber and the liquid phase outside, provides high surface area for maximum efficiency for gas removal processes. One such design encloses the hollow fiber array within a pressure vessel, which includes an internal baffle to promote turbulent flow and mass transfer. An example of this equipment is shown in Figure B-2.

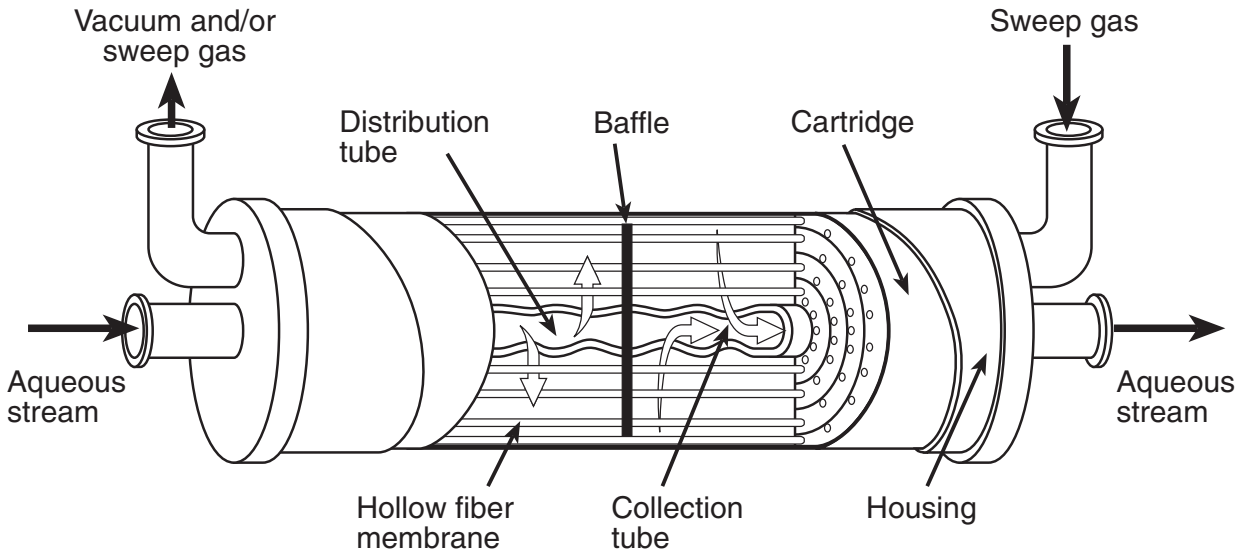


Figure B-2
Components of a GTM Unit

By altering the partial pressure of a gas at the air/water interface, a driving force is created which results in the mass transfer of a gas into or out of solution. There are three ways to alter the partial pressure of a gas in a GTM system:

- Apply a vacuum to the inside of the hollow fiber
- Use a "sweep" gas, usually nitrogen, which effectively lowers the partial pressure of other gases such as oxygen and carbon dioxide
- Use both a vacuum and a "sweep" gas

The effectiveness of this membrane technology is governed by several factors:

- Water flow through the system
- Water temperature
- Amount of vacuum applied
- Volume and purity of the sweep gas

GTM systems can be skid mounted and installed easily in a minimum of space. One such system[5] consists of two 1x1x1 (3 in series) arrays on two skids which produce a combined effluent of 200 gpm (760 L/m) at 15 ppb (or less) of dissolved oxygen. The two skids each occupy less than 370 cubic feet (10.5 m^3) of space.

The GTM process is installed on a variety of systems ranging from 0.5 gpm to over 2500 gpm.[6,7]

Overall costs in US dollars for the GTM process are estimated to be about $0.70 to $1.30 per 1000 gallons ($0.18-$0.34 L) depending on the degree of oxygen removal required and the systems flow rate.

B.3.1 Early GTM Applications Experiences

With a suitably designed system, oxygen levels of less than 1 ppb in the effluent water stream are said to be achievable. An example of a GTM system used to remove oxygen from boiler feed water at a petroleum refinery [8] is shown in Figure B-3. In this case, two parallel trains of GTM units are provided, each having 10 inch (25.4 cm) membrane contactors connected in series. The nitrogen sweep gas is 99.9% pure, and flows at a rate of 1.5-2.0 scfm. Vacuum requirements are ~ 25 acfm at 28 inches (71 cm) of mercury. The 200 gpm (760 L/min) of product water contains less than 15 ppb of dissolved oxygen.

An example of a hybrid system employing GTM for carbon dioxide removal followed by catalytic oxygen removal [9] is shown in Figure B-4. This is an outsourced treatment plant in use at a nuclear facility.

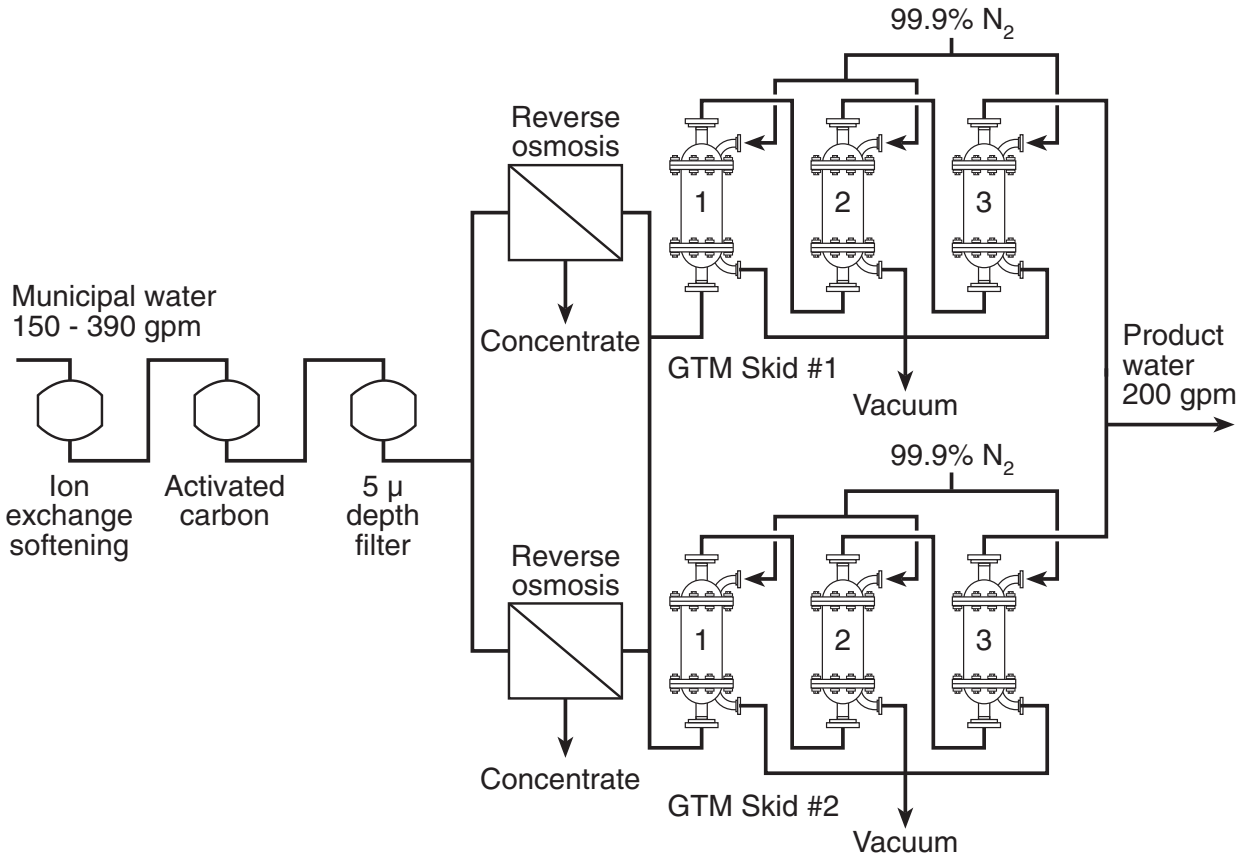


Figure B-3
GTM System Process Flow Diagram (Note: 1 gal = 3.785 litres)

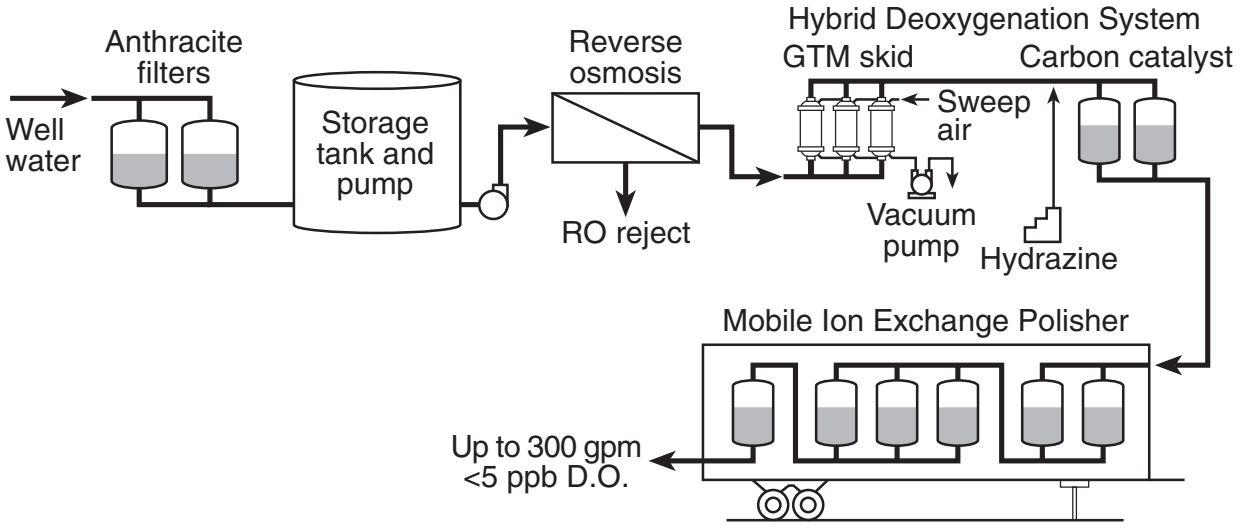


Figure B-4
GTM System Process Flow Diagram (Note: 1 gal = 3.785 liters)

This GTM system consists of three skid-mounted contactors in parallel, a vacuum pump, valving to allow an air sweep, and instrumentation to monitor vacuum level and air sweep volume. The membrane system is primarily for carbon dioxide removal, but also removes some oxygen. (The use of an air sweep rather than nitrogen probably limits the extent to which oxygen can be removed in this part of the system).

Hydrazine injection occurs at the GTM effluent using a small, diaphragm positive displacement pump. Any remaining oxygen in the RO permeate water reacts with the hydrazine as it passes through two activated carbon vessels connected in parallel. The water then enters a three-bed ion exchange system for further polishing. This system consists of a strong acid cation, strong base anion and a mixed bed unit.

This hybrid system produces up to 300 gpm (1136 L/m) of purified water at less than 5 ppb of dissolved oxygen. It is significant to note that the deoxygenated water is stored in a tank with a nitrogen blanket. The tank effluent is tested daily for dissolved oxygen, which consistently measures below 5 ppb.

A southwestern electric utility plant chose to utilize gas transfer membrane technology (GTM) to reduce their dissolved oxygen levels to below 20 ppb prior to their demineralized water storage tank[10]. Their system consists of conventional ion exchange plus GTM to produce 500 gpm (1894 L/m) of demineralized and deoxygenated water to storage. A unique feature of this system is that the GTM is located after the strong acid cation and before the strong base anion unit. Thus, the GTM is acting as a replacement for a forced draft decarbonator to remove the carbon dioxide generated in the strong acid cation unit. Locating the GTM at this point appreciably reduces the load on the anion unit while also removing oxygen.

Another innovative use for GTM systems involves minimizing oxygen ingress to an existing demineralized water storage tank at a nuclear power generating facility[11]. In this installation the inlet water to the tank has been previously deoxygenated to less than 10 ppb. The tank is equipped with a bladder to minimize oxygen ingress. However, without continuous oxygen removal, storage tank dissolved levels would gradually reach 1-2 ppm or greater. A GTM system was installed on a constantly recirculating “kidney loop” in a full-flow 100 gpm (26 L/m) pilot plant test. Dissolved oxygen levels in the storage tank were then consistently maintained to less than 10 ppb.

The conclusion reached from the full flow pilot plant test was that a recirculating GTM system is a viable alternative to installing a nitrogen blanket, floating roof or diaphragm for maintaining low levels of dissolved oxygen in a storage tank.

B.3.2 Use of GTM Systems in Combined Cycle Units

In general, combined cycle plant designs make no special provision for removal of treated makeup as part of the treatment process or in storage tanks. However, operating experience and the requirement that many combined cycle units be operated in cycling/peaking service has resulted in considerable interest in GTM technology, with some plants now employing it or considering its installation and use.[12-14]

Lincoln Electric System (LES) owns and operates three combustion turbine (CT) units which operate with natural gas or fuel oil at the Salt Valley Generating Station (SVGS). Two of these units can operate in a combined cycle configuration; each unit has a heat recovery steam generator (HRSG) that removes heat from the CT exhaust gas and generates steam that is used to generate power from a steam turbine.

The combined cycle units at SVGS were designed for cycling service operation. During summer peak demand, it is common for the combined cycle units to operate during the day and shut down each night. At other times, the units are not normally in service except as needed to meet system (customer) power demands or to supply power to the grid. Thus these units are subject to both frequent overnight outages and extensive idle periods. However, it is important that the units be capable of rapid return to service without impacts on their long term availability.

Makeup water to the combined cycle units is produced on-site and is stored in an outdoor 225,000 gallon (850 m^3) stainless steel storage tank that is vented to atmosphere. It is produced from effluent water discharged from the City of Lincoln's Northeast Waste Water Treatment facility. The makeup water treatment system consists of two multi-media filters, two ultra-filtration skids, two two-pass/two-stage reverse osmosis skids, one electro-deionization skid, and two mixed bed ion exchangers.

Treated makeup is transferred from the outdoor storage tank to two, 15,000 gallon (56.8 m^3) condensate storage tanks (CSTs). The CSTs are located indoors and are vented to atmosphere. They supply the makeup water to the combined cycle portion of the plant based on low condenser hotwell water level. The tanks also periodically receive "dump" water from the condenser hotwell during plant startups and shutdowns. This water is treated with ammonium hydroxide. The cycle includes a deaerating condenser with redundant vacuum pumps, which represents the only means of oxygen removal.

Best operating practices at SVGS require that dissolved oxygen at the condensate pump discharge from the hotwell to the HRSGs be less than or equal to 7 ppb and the cation conductivity be less than or equal to 0.3 µS/cm.[12] These requirements become difficult to meet when the hotwell makeup valve cycles open and closed admitting air saturated water from the CST's. As a result, dissolved oxygen (DO) levels have been observed to spike from < 10 ppb to between 70 and 100 ppb and often do not stabilize before the make-up valve reopens. Feedwater cation conductivity is rarely less than 0.3 µS/cm due to entrained carbon dioxide (CO_2).

When filling empty HRSGs for cold startup or when making up during hot or warm startups, it is generally necessary to supply the HRSGs with air saturated water, which is recognized to be undesirable.

In view of these observations and concerns, LES personnel initiated action to identify, evaluate and compare possible remedial measures that would minimize the effects of air in the makeup water on cycle chemistry during cycling service and startup operations.[12] Specific needs were to be able to remove oxygen during transfer from the CSTs to the units during service and to remove oxygen from water in storage prior to filling empty HRSGs and other combined cycle system components. Two technologies were evaluated for oxygen removal. The first, nitrogen

sparging, strips oxygen and other non-condensable gases from water in storage. This system can also be used to create a nitrogen cap or blanket over the water, thus preventing entry of air through the vents. The second technology, gas transfer membranes (GTMs), can remove oxygen from water during transfer or, with suitable piping and pumping, can remove oxygen from water in storage. Based on considerations of technical performance, operational flexibility and costs, the GTM system was selected for use at SVGS.

At the time of publication, final system specifications were being developed.[12] LES had previously investigated prepackaged GTM systems and provision of GTM treatment from a service organization and ultimately decided to purchase the membrane contactor assemblies and mounting hardware directly from the manufacturer. The on-site skid, piping, valves, instrumentation and controls will be engineered, installed and tested by LES personnel. The time interval from ordering of equipment to initial system operation is estimated to be about 90 days. The system design will utilize both a vacuum pump and application of nitrogen sweep gas to remove oxygen from the water. The system will be sized to match the flow rates of the pumps used to transfer condensate from the CSTs to the hotwells of the units. It will also include a recycle capability to allow deoxygenation of water to be used to fill equipment for cold startup.

B.4 Makeup Water Storage

The results of oxygen removal by any of the above are completely negated if the makeup water is stored in tanks, which are vented to atmosphere. There are several ways that tanks can be equipped to prevent air ingress:

- Plastic or rubber diaphragms
- Floating covers
- Nitrogen positive pressure purging

The use of plastic or rubber diaphragms to protect condensate storage tanks from oxygen ingress has been very limited in the electrical generating industry. This is the result of relatively high installed costs, high maintenance costs and the fear (perhaps justly so) that the diaphragm might fail causing a major disruption in power plant operations. Also, diaphragms would be difficult, and possibly impossible to install in existing tanks.

Floating covers have been in use, especially in petroleum refinery tanks, for many years. Their purpose in this case is to prevent undue evaporation of volatile liquids. Here again, installation of floating covers has not been popular at electrical generating plants for some of the same reasons as given above for diaphragms. Backfit of floating covers on existing condensate tanks, while perhaps possible, would certainly require considerable engineering and would undoubtedly be quite expensive.

As described earlier, GTM systems have been applied to control dissolved oxygen levels of water in storage. Another effective means to prevent oxygen ingress to makeup and condensate storage tanks is to provide a nitrogen blanketing system. Such a system is relatively easy to install on existing tanks and inexpensive to operate, given the low cost of nitrogen and the modest amount of nitrogen required.

One such system[15] is shown in Figure B-5. This system has a nitrogen bottom sparger (A), inlet pipe sparger (B), nitrogen supply and controls (D), oxygen or conductivity analyzer (F), tank pressure control (C), and an overflow pipe (E). The sparging itself is through sintered stainless steel sparging elements. Two pressure regulators control the nitrogen pressure to the spargers; one for the bottom sparger and one for the inlet pipe sparger. This is followed by a passive critical orifice flow element. This element prevents the nitrogen flow from exceeding the capacity of the tank pressure control siphon, which vents the excess pressure.

By placing a sparger in the inlet water supply line to the tank, any residual dissolved oxygen in that water should be effectively removed. Providing a second sparger in the bottom of the tank will prevent the ingress of air.

The following costs are updated cost estimates[15] for the system shown in Figure B-5 in year 2005 US dollars:

Capital Cost: $23,000 to $33,500.

Installation Cost: $6,000 to $11,500.

Nitrogen Consumption Costs: $120 per month assuming storage tank inflows and outflows are not excessive.

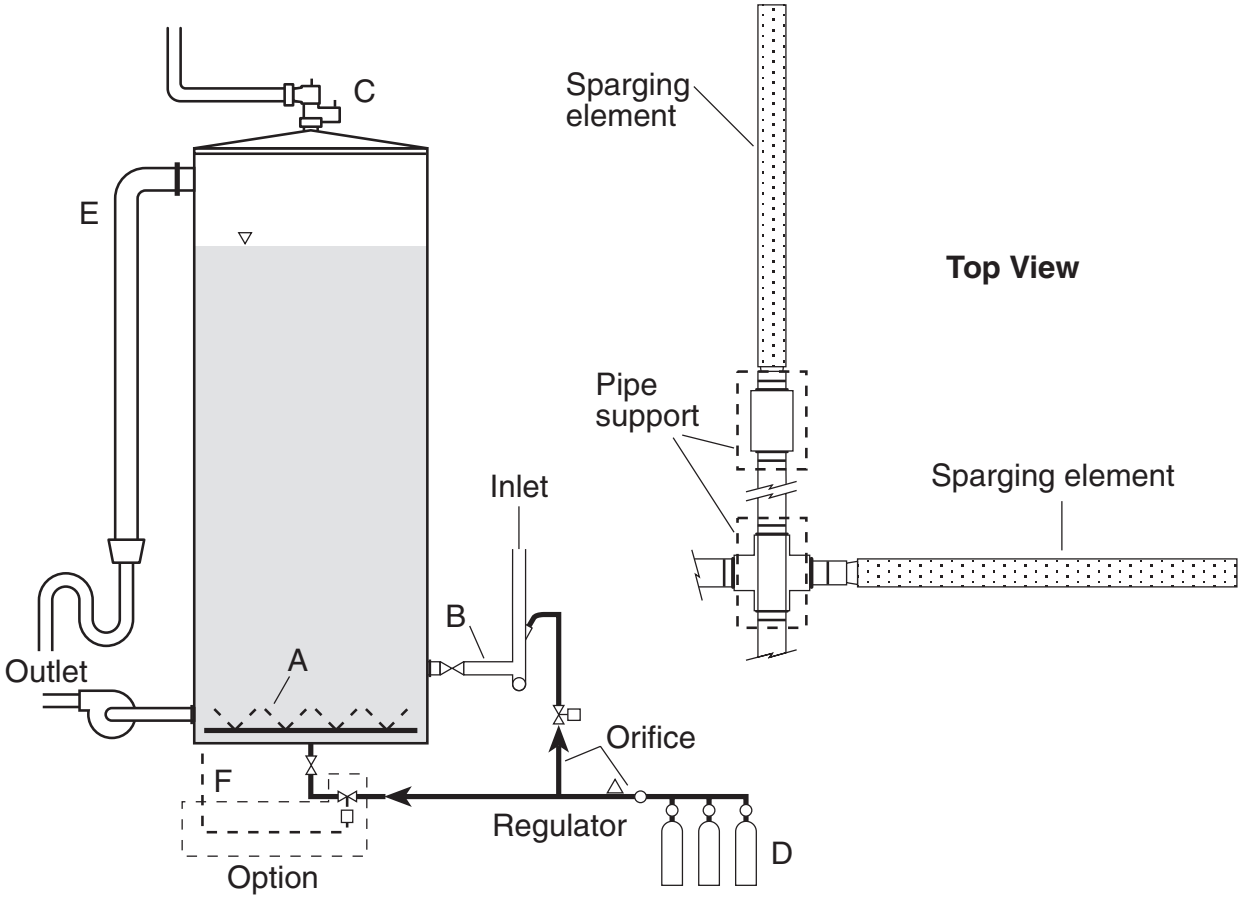


Figure B-5
A Storage Tank Nitrogen System and Sparging Elements[15]

The system in Figure B-5 would most probably use cylinder nitrogen, because of the relatively low consumption. The purity of cylinder (or cryogenic) nitrogen is 99.995%.

Other, simpler nitrogen blanketing systems merely provide a slight positive pressure in the storage tank by using a small continuous flow of nitrogen applied at the top of the tank. This design, as compared to the above, probably requires a larger consumption of nitrogen and lacks the obvious advantage of the purge system for incoming water to the tank.

While removal of oxygen from makeup may appear costly at first glance, it is essential to the proper control of iron and especially copper in the feedwater cycle. In the overall picture, the use of deaerated makeup water will produce savings, since corrosion and iron oxide transport will be reduced.

B.5 References

1. Utility Survey Results. Proceedings: Sixth International Conference on Fossil Plant Cycle Chemistry, EPRI, Palo Alto, CA: 2001. 1001363.
2. Utility Survey Results. Fifth International Conference on Fossil Plant Cycle Chemistry, EPRI, Palo Alto, CA: 1997. TR-108459.
3. S. Dominick, U.S. Filter Corporation, Personal Communication to A. Aschoff, August 2000.
4. R. C. Dickerson, W. S. Miller. U. S. Patent 4,556,492, "Deoxygenation Process". December 3, 1985.
5. Ecolochem, Inc. Application Bulletin, December 5, 1999.
6. D. Schwarz, "TOC Reduction Using Membrane Technology", *Ultrapure Water*, October 2000.
7. T. Dang, D. S. Huntsberger and B. A. Kitteringham, "Using Membrane Contactors for CO_2 Removal to Extend Resin Bed Life", *Ultra Pure Water*, July/August 2003.
8. P. H. Kinghorn and W. E. Haas, "Low Level Deoxygenation of Boiler Makeup Water Using Gas Transfer Membranes". *Proceedings of the International Water Conference*, p. 527, October 18-20, 1999.
9. S. B. Gorry, W. E. Haas, and J. W. Mahaffee, "Effective Deoxygenation by a Process Combining Gas Transfer Membranes with Catalytic Oxygen Reduction". *Proceedings of the International Water Conference*, p. 535, October 18-20, 1999.
10. R. M. Mode, W. E. Haas and W. Greene, "Dissolved Oxygen Reduction by Membrane Technology to Reduce Feed Water Corrosion". *Proceedings of the International Water Conference*, p. 406, October 20-24, 2002.
11. J. Helmrich, W. E. Haas and J. E. Staton, "Maintaining Storage Tank Dissolved Oxygen Levels Utilizing Gas Transfer Membranes". *Proceedings of the International Water Conference*, p. 207, October 22-26, 2000.
12. Personal communications between D. Dixon, Lincoln Electric System and K. Shields, December 2005.
13. Personal communications between P. Pye, SCANA and K Shields, January 2006.
14. Personal communications between H. Campbell, Progress Energy and K. Shields, January 2006.
15. O. Jonas, Jonas Inc., Personal communication with A. Aschoff, April, 2000.

C
AIR IN-LEAKAGE MONITORING AND CONTROL

C.1 Cycle Air In-Leakage

Continual vigilance must be exercised to prevent air in-leakage to the cycle from those equipment elements under vacuum at any or at all times. Particular problem areas include pump seals, LP turbine shaft seals, valve bonnets, threaded joints, and especially the expansion joint between the turbine and condenser. Monitoring the amount of air in-leakage (flow to the vacuum pumps) is essential for proper control of oxygen and carbon dioxide. Such monitoring will determine when an exhaustive effort must be made to find and fix the source of air leakage.

The Heat Exchange Institute recommends that air in-leakage be restricted to no more than 1.0 scfm per 100 MW (1.7 sm^3/h per 100 MW) of generating capacity. This same value has been included in many EPRI Cycle Chemistry Guidelines. Current guidelines, including the revised chemistry guidelines for combined cycles[(1)] include air in-leakage as a core monitoring parameter that should be monitored continuously or once per shift. Maintaining a tight system with low levels of air in-leakage is necessary to meet the EPRI target value for dissolved oxygen in condensate (10 ppb).

EPRI survey results from 2003[(2)] clearly indicate that organizations operating fossil plants place varying levels of importance on cycle air in-leakage. About 60% of the respondents indicated that air in-leakage is checked continuously or once per day. The remainder indicated it was only checked weekly or “as needed”.

This appendix reviews available air in-leakage measurement methods and techniques used to pinpoint locations at which air in-leakage is occurring.

C.2 Rotameters

Excess air in-leakage not only affects corrosion, metal oxide transport and subsequent deposition, but can also increase turbine backpressure, which directly reduces electrical generating capacity. A complete analysis of the effects of air in-leakage on condenser efficiency was made [(3,4)] using a multisensor probe. This multisensor probe and its use in measuring air in-leakage are further described later in this Section C.3.

A rotameter located at the exhaust of the steam jet air ejector or mechanical vacuum pump is often used to quantify condenser air in-leakage. This was the standard approach at the time older fossil plants were designed and constructed. Manual readings were planned to be taken, normally once a shift or at least once a day, however, manpower levels often restrict this. Air in-leakage can increase and remain at potentially damaging levels for hours or possibly days before the

increased level of in-leakage is discovered, since turbine backpressure may not have increased significantly or noticeably.

Under certain conditions, rotameters provide adequate flow rate measurements of air in-leakage. However, many factors can affect the accuracy of the readings so obtained, such as debris, exhauster pulsations, water carryover, etc. Rotameters also have limited range, generally 10:1. Therefore, most problematic air in-leakages cause the rotameter to be pegged against the high level stop. Rotameters generally receive very little maintenance and are checked very infrequently at many plants. In these situations, the operator has no idea of the extent of the air in-leakage, given the fact that the turbine backpressure rise may appear to be rather small and insignificant.

In an attempt to mitigate these inherent problems with rotameters, a series of instruments were developed which featured continuous readouts of air in-leakage. These early continuous measurement devices had some serious drawbacks, such as not being able to distinguish between water vapor and air; and, operating under the principle that the condenser exhaust gases were always at saturation, when in fact, they were not.

C.3 Multisensor Probe

Subsequent development efforts have resulted in commercially available instrumentation, which apparently has overcome the limitations of earlier designs. One such instrument features a multisensor probe (MSP), which is installed in the exhaust line between the condenser and air removal equipment. This device is depicted in Figure C-1.

This instrument directly measures mass properties of the mixture of water vapor and non-condensable gases in the air removal line from which individual gas properties are discerned using thermodynamic computations. The instrument is essentially a gas analyzer and total mass flow meter. By measuring velocity, pressure, temperature, and relative saturation, the instrument can separate the mass flow of non-condensable gas and water vapor from the combined properties of the mixture. As a result, several important and useful properties of the gas flowing in the exhauster suction line are determined, as summarized in Table C-1.

Table C-1
Summary of Parameters Determined with the Multisensor Probe System

- Air In-leakage
- Volumetric Flow
- Total Mass Flow
- Water Vapor Mass Flow
- Water Vapor/Air Mass Ratio
- Relative Saturation
- Water Vapor Density
- Air Density
- Total Pressure
- Partial Pressure of H_2O Vapor
- Partial Pressure of Air
- Temperature

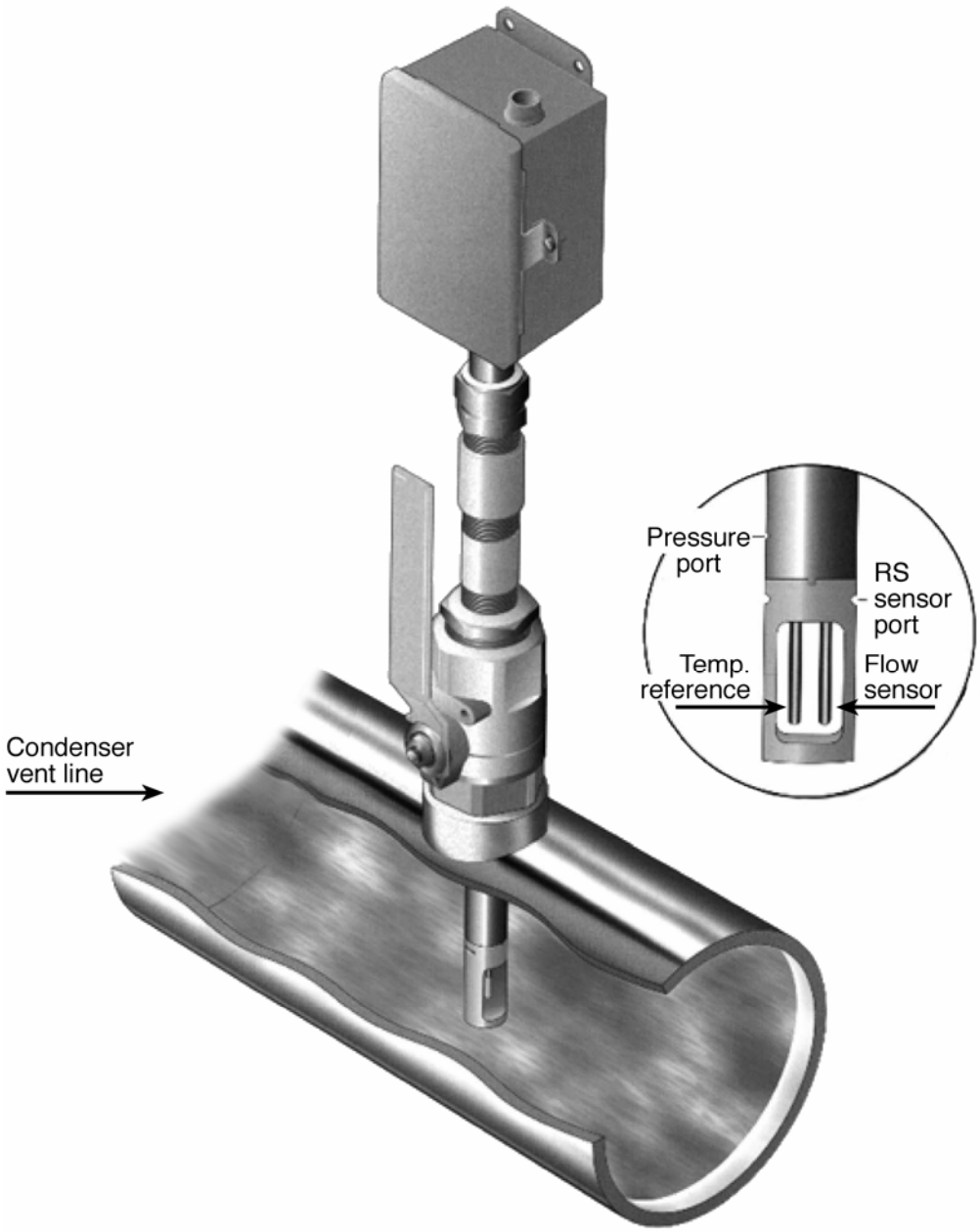


Figure C-1
Multisensor Probe (courtesy of Intek, Inc)

Air in-leakage, as measured by the MSP[3], is the sum of all leak sources entering the subatmospheric pressure system and subsequently flowing through the exhauster line upstream of the sensor location. The MSP measures the exhauster capacity (ACFM), which is useful to gauge the effectiveness of the exhausters to remove the gas mixture from the condenser. The

MSP, however, does not measure air entering the low pressure system near the condensate pump, such as at suction valves, input connections, and shaft seals.

Evaluation and analysis of condenser performance and measurement of in-leakage is best accomplished with the use of more than one probe in the MSP system, as shown in Figure C-2. Each probe is identified by a number that is used to record performance information and to help pinpoint possible leak locations, since air in-leakage is removed primarily through the condenser air removal section closest to the leak. As illustrated in Table C-1 and Table C-2, for a single bundle two-shell condenser, a self validating arrangement can be established that will allow the accuracy at all probe locations to be verified.

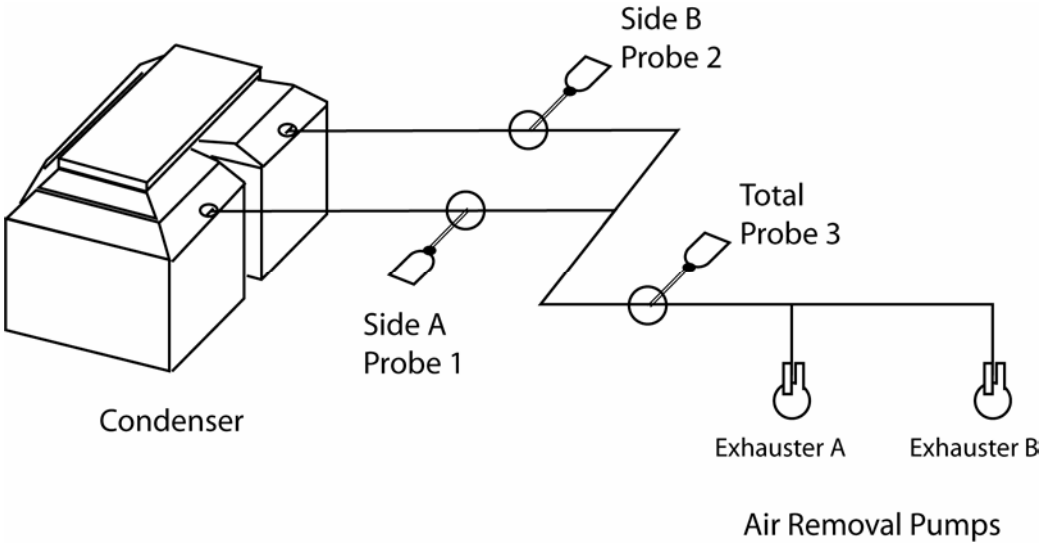


Figure C-2
Validating Arrangement Multisensor Probe Instrument Schematic

The probe marked “Total” measures flow into the vacuum pump (or air ejector) and distinguishes between air flow and water vapor flow, making it possible to quantify the performance of the condenser’s exhausting equipment. A measurement at the pump (or air ejector) discharge cannot provide this information. This probe also measures the sum of flow from the A and B condenser shell, providing verification of calibration accuracy of the system.

A multi-probe arrangement provides information that narrows the search for leak sources to a specific region of the condenser[3,4]. The following chart illustrates how the three-probe, validating arrangement of Figure C-2 would react to various leak locations or failed/faulty exhauster. Use of additional probes, strategically deployed, can improve detection capabilities.

Table C-2
Examples of a Three-Probe Air In-leakage Measurement System (1 scfm = 1.7sm^3/h)

Leak Location	Probe Indications and Plant Dissolved Oxygen (DO)
Low, equal leak on both sides and exhauster in good operating condition	Normal DO. For Mass flow, SCFM, ACFM: Side A = Side B Side A + Side B = Common Total Mass Flow 200-600 lb/hr Mass Ratio >3 at all locations
Side A	Possible elevated DO. For Mass flow, SCFM, ACFM: Side A > Side B Side A + Side B = Common Side B normal SCFM but very low mass flow
Side B	Possible elevated DO. For Mass flow, SCFM, ACFM: Side A < Side B Side A + Side B = Common Side A normal SCFM but very low mass flow
Faulty Exhauster Note: Exhauster capacity can be compared by running 1 pump at a time	Possible elevated DO. For Mass Flow, SCFM, ACFM: Side A = Side B, but low mass flow & ACFM Side A + Side B = Common Lower than normal Total Mass Flow Mass Ratio <3 at all locations
Center joint seal, loss of gland steam, or other central location high in condenser hood	Possible elevated DO. For Mass Flow, SCFM, ACFM: Side A = Side B with SCFM high Side A + Side B = Common Mass Ratio <3 at all locations

Table C-3
Some Examples of Observed *RheoVac* Monitor Measured Data and Corresponding Identification of Leak Presence and Leak Location Determinations (1 scfm = 1.7 sm^3/h)

Conditions	Probe Indications of Air In-leak (SCFM)
Normal tight system	1 = 2.5 SCFM 2 = 2.5 SCFM 3 = 5 SCFM
Abnormal, need to locate and fix leaks (dogbone joint seal). Condenser pressure elevated.	1 = 15 SCFM 2 = 18 SCFM 3 = 33 SCFM

C.4 Air In-Leakage Source Identification Methods

Rotameters only provide an indication of the magnitude of air passing through the air removal system piping. The use of the MSP is helpful in determining the extent of air in-leakage and providing some guidance relative to where, generally, leaks may be occurring. After initial assessment efforts, it is then necessary to further determine the exact location of the leak(s). The primary method typically used for this purpose is inert gas leak detection, by use of a sophisticated analyzer in conjunction with the selected tracer gas. Other techniques, including ultrasonic detection and infrared detection have also been considered and seen limited use.

C.4.1 Inert Gas Methods

Air in-leakage testing is done by drawing a sample of condenser off-gas from the exhauster discharge while releasing the tracer gas at those areas within the vacuum boundary where leaks may be expected to occur. Since the condenser is under vacuum, the tracer gas migrates into the condenser shell, and from there it is removed by the air-removal system. A leak is identified when an off-gas sample containing the tracer gas passes through the analyzing equipment and is detected.

Some early work in this area involved the use of Freon as the tracer gas. However, use of Freon was subject to environmental concerns and interest subsequently moved to alternative gases.

Helium has been used as a tracer gas successfully in determining air leaks for many years. The testing is accomplished by injection of helium at various locations (within the vacuum boundaries) and detection of helium in the condenser off-gases by use of helium mass spectrometry. This system is still in use today as the most widely used technique for detecting air in-leakage. There are some limitations to the use of this technique, however, particularly as regards sensitivity of response, which is particularly important in the detection and evaluation of very small leaks.

Other tracer gases have been investigated to address the limitations of helium leak detection. There has been considerable interest in sulfur hexafluoride (SF_6) as it offered advantages over helium. EPRI initiated research activity to investigate and develop the use of SF_6 as a tracer gas in the 1980s. The fundamental advantage of sulfur hexafluoride (SF_6) was that it could be detected in very low concentrations, as low as 0.1 ppb. By contrast, the lowest detectable concentration of helium is about 1 ppm. SF_6 analysis is about 10-100 times more sensitive than helium detection. Field testing experience showed that each tracer gas had attributes that could make it the better choice in specific circumstances.[5]

Recognition of SF_6 as a greenhouse gas has raised some concerns within some organizations about regulatory restrictions on its use within some organizations. However, the technique is still available and in use. Users of these guidelines interested in use of SF_6 are advised to determine if there are any organizational policies which may prohibit or restrict its use.

The determination of air in-leakage using tracer gases requires a great deal of experience and a considerable outlay of capital if the necessary equipment is to be purchased. Some organizations have elected to make the necessary investments in equipment and training of personnel. There

are, however, service and consulting firms specializing in the on-site evaluation of air in-leakage. These firms have their own equipment and are well versed in this technology. Updated estimates suggest a typical plant assessment would likely cost between about $3500 and $5000 (US dollars)[(6)]; in cases where air in-leakage is affecting plant performance, experience has shown that the associated benefits (above and beyond those related to the chemistry) of prompt detection and correction of air in-leakage sources can result in very short payback periods.

C.4.2 Ultrasonic and Infrared Techniques for Air In-leakage Detection

These techniques have seen some use in air in-leakage detection.[(7)] Limitations associated with the methods have served to constrain their acceptance within industry.

Ultrasonic detection has been successfully used for detecting air leaks. Pressurized leaks are fairly easily located using ultrasonic listening devices, however, vacuum leaks are reportedly somewhat harder to find.[(8)] Shielding or "blocking" suspect areas from background noise will improve the evaluation.

Air inleakage seen through an infrared camera will appear as a cool area surrounding a void. However, if the component surface and the ambient temperature are similar, the area will likely go undetected when using this technology.

C.5 Fossil Plant Air In-Leakage Management Strategies

Typically, air in-leakage in power plants is managed by one of the available tracer gas techniques.

C.5.1 Leak Detection Using Helium

One large US utility has developed a formal program to control air in-leakage at each of their power plants [(9)]. The program starts with a comprehensive written procedure which is continuously updated as new information is forthcoming and new experiences noted. The program and its revisions are controlled by central staff and implemented at each plant by the plant's performance engineering group. Formal training is given to each participant in the program.

The program is based on a daily monitoring and recording of air in-leakage at the vacuum pump or steam jet air ejector exhaust. The instrument presently in use for this purpose is a thermal gas mass flow meter, costing in the range of $2200 to 3200 each. Air in-leakage at the utilities' various plants is normally in the range of 2–10 scfm/ 100MW (3.4-17 sm^3/h/100 MW), depending upon unit size, configuration, etc. In addition, close attention is paid to unit backpressure, an increase of which could indicate increased air in-leakage. Continuous readings of dissolved oxygen at the condensate pump discharge are carefully reviewed as another indication of increased air in-leakage.

At the first indication of increased air in-leakage (above the established base, increased backpressure, higher dissolved oxygen), a leakage test is initiated. An important part of the program is the establishment of a checklist, which delineates all of the various sampling points and their location at each plant elevation. For example, the turbine room sample points are broken down by directions- north, south, east and west relative to the turbine.

The equipment used for air in-leakage detection is a helium mass spectrometer. The detector is located at the vacuum pump or steam ejector exhaust. A unique feature of the program is the use of a wireless video camera, which constantly focuses on the readings of the air in-leakage detection unit. The results (leakage or no leakage) are transmitted to the operator via a remote wireless receiver. Thus, only one person is required to conduct a test, minimizing manpower.

The detection instrument has an internal vacuum pump and requires a dry sample for proper operation. The inlet sample tubing is passed through a cooling coil embedded in ice, followed by two water traps in series prior to entering the instrument.

Tests start at the top of the unit, working down, since helium, being lighter than air, will rise. If testing started at the bottom of the unit, the rising helium would be sucked into leaks further up, severely hampering interpretation of results.

Most tests are conducted at medium, or preferably, at full load, to maximize condenser vacuum and, subsequently, potential air in-leakage. At times, however, it is necessary to test at low loads to determine leakage at those areas of the low end of the cycle that are under pressure at high loads but under vacuum at low loads. An example would be the low pressure feedwater heaters.

Some examples of sampling points which are emphasized in the test procedure are condenser and condensate pump expansion joints, various flanges and pipe fittings, turbine horizontal shell flanges, turbine rupture diaphragms, turbine shaft seals, various turbine penetrations, pipe plugs, valve packings, etc.

Helium is sprayed at each test area at low pressure, about 10 psi (70 kPa), for only about 2-3 seconds to prevent too much helium from escaping, which could result in false readings and misinterpretations. It is necessary to note any extraneous air currents at a particular sampling location to prevent helium from “spreading out” and causing false leak indications.

Generally, to save time, a group of adjacent test points are sprayed with helium at the same time. If there are no leaks found, the next group of test points is sprayed. However, if leaks are recorded, further tests are required to isolate the offending location. A record of leak location is made together with the relative intensity of the leak.

Another practice, which is followed on a periodic basis, about once per year, is to flood the condenser with water to above the tube sheet and to look for water leaks from possible cracks in the condenser shell, attached piping welds or valve packings. Before performing this operation it will be necessary to determine explicitly whether the structural supports provided are sufficient to hold the extra weight of water within the condenser.

Results of all testing are submitted to the maintenance staff at the plant for necessary repairs, replacements, etc.

This program has been very effective in reducing oxygen and carbon dioxide from entering the cycle. Corrosion and corrosion transport have been reduced substantially since the program has been initiated.

C.5.2 Leak Detection Using Sulfur Hexafluoride

A similar approach to that described for helium could be used with SF_6, subject to consideration of organizational policies on use of this material.

The sensor technology for SF_6 is based on the principle of electron capture[10]. To remove oxygen from the gas sample, hydrogen gas is introduced. This mixture enters a catalytic reactor in which the hydrogen and oxygen react to form water. Figure C-3 is a general view of the SF_6 analyzer while Figure C-4 is a schematic diagram showing how the off-gas sample passes through the analyzer.

As indicated earlier, SF_6 can generally be used successfully wherever helium can be used, although the converse may not always be true and there are situations in which use of helium is preferred[5]. The following guidelines may be applied:

- If unit air in-leakage is in excess of 10 CFM, either gas may be used. If less, SF_6 is preferred.
- If the unit is running at greater than 20% turbine power, either gas may be used. If the unit has no turbine power and the leak is so bad that the unit can not be brought up to any turbine power level, standard procedure would dictate the use of helium.
- The search for the cause of air leakage below the steam space requires the use of SF_6 as the standard procedure.
- Inspections of units of less than 50MW capacity (steam turbine) should always use helium.

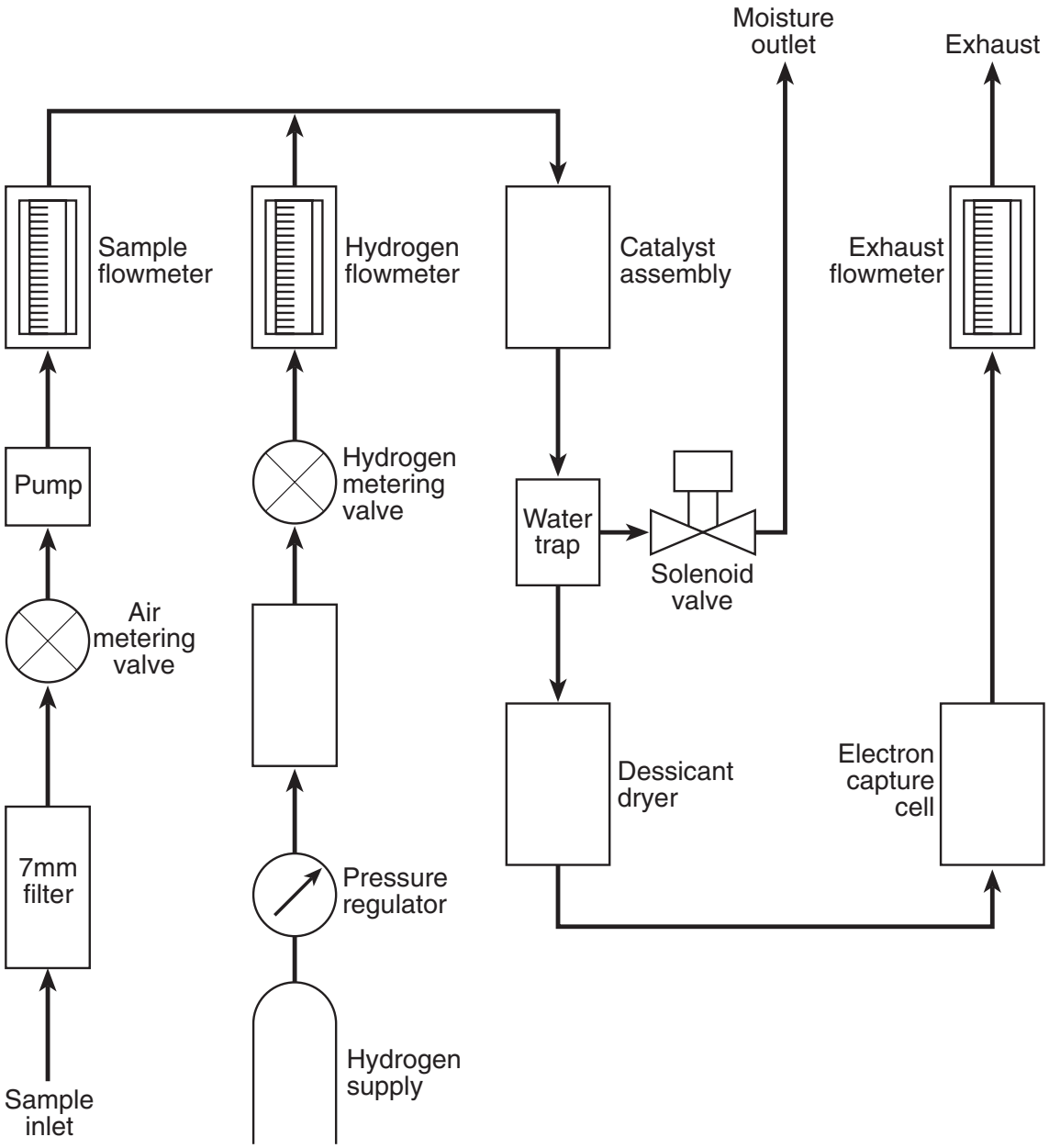


Figure C-3
Flow Schematic for SF_6 Analyzer System

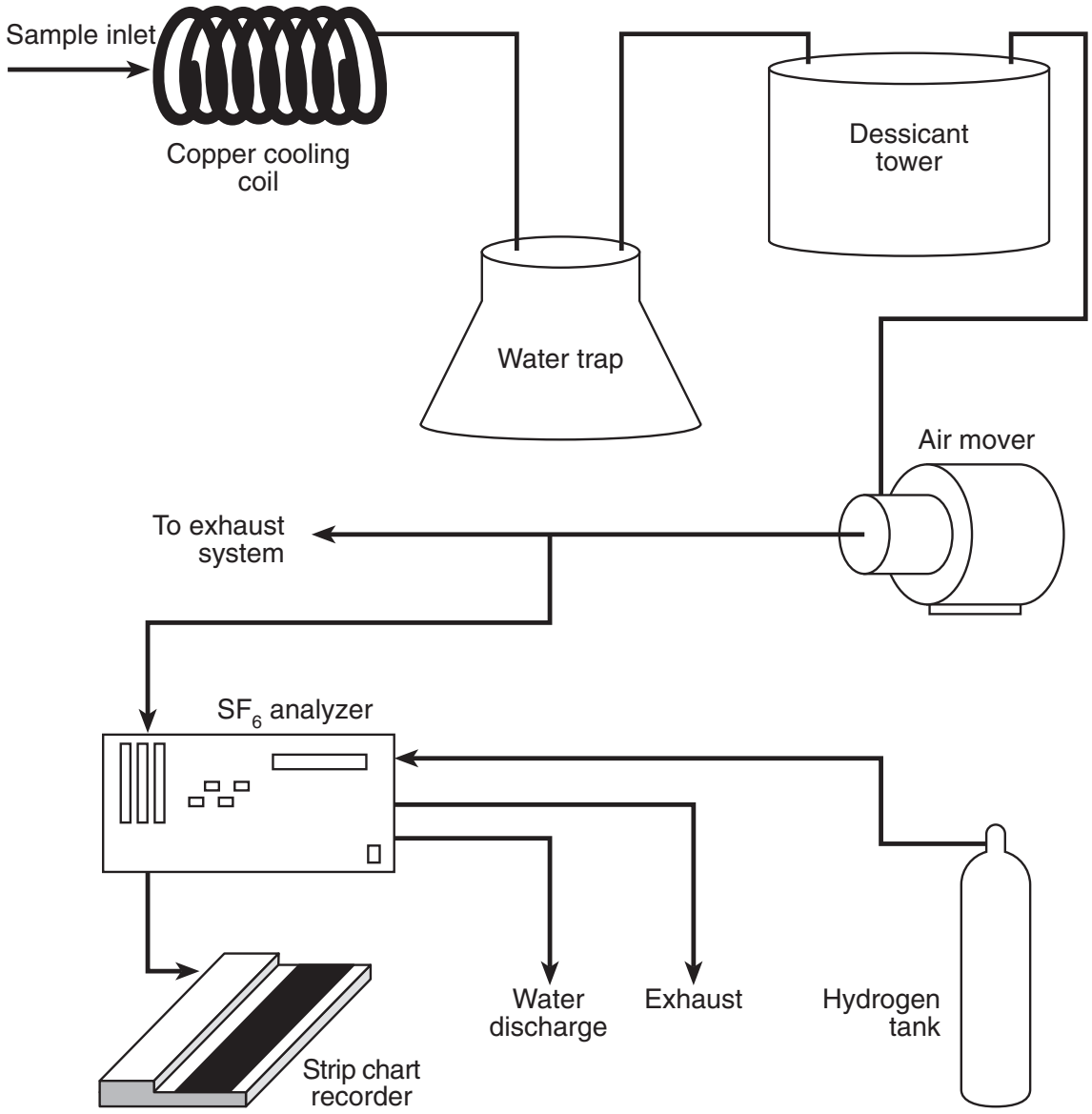


Figure C-4
Schematic Diagram of SF_6 Sampling System

C.5.3 Use of Multisensor Probe System

Another utility experience highlighting the economic value of finding and repairing air leaks was reported at an EPRI Conference[8].

Other plants manage air in-leakage through use of multisensor probe (MSP) Systems[4,11], which may incorporate a thermal gas mass flow meter and other sensors as previously described. Its reported advantages over any exhauster discharge measurements are: freedom from inadvertent high output spikes or oscillations; measurement of exhauster capacity degradation caused by shaft seal leaks, wear or regulation; measurement of the water vapor to air mass ratio which

triggers the onset of increased condenser pressure caused by air in-leakage and by high resolution measurement of air in-leakage and other non-condensable gases being removed from the condenser.

Assessment of the understanding of the shell side dynamics of condensers[11,12] has shown that condenser defects can cause air blanketing or binding, affecting the condenser's effective heat transfer coefficient. These regions are subcooled and have a significant concentration of non-condensable gases with high partial pressure. Therefore, if present they can contribute greatly to dissolved gases and corrosion even though measured air in-leakage is low.

C.6 References

1. Cycle Chemistry Guidelines for Combined Cycle/Heat Recovery Steam Generators (HRSGs). EPRI, Palo Alto, CA: 2006. 1010438.
2. Utility Survey Results. Proceedings: Seventh International Conference on Cycle Chemistry in Fossil Plants, June 3-5, 2003, Houston, Texas, EPRI, Palo Alto, CA: 2004. 1009194.
3. J. W. Harpster, Intek Inc., "On Understanding Mechanisms that Control Dissolved Oxygen in Condenser Condensate." *Proceeding of the 21st Annual Electric Utility Workshop*, University of Illinois, Champaign, IL, May 8-10, 2001.
4. W. H. Stroman and J. W. Harpster "Continuous Monitoring for Condenser Air In-Leakage" Presented at the 2002 Spring Meeting, ASME Research Committee on Power Plant and Environmental Chemistry, Charleston, SC, March 11-13, 2002
5. *Condenser In-Leakage Guideline*. Electric Power Research Institute, Palo Alto, CA.: TR-112819, 2000.
6. La Porte, Conco Services Corp., Personal Communication to A. Aschoff, April 2000.
7. Condenser Tube Failures, Theory and Practice, Volume 1, Fundamentals. EPRI, Palo Alto, CA: 2006. 1010188.
8. W.A. Kaufman, "Experiences with Steam Cycle Air Ingress at Alliant Energy Fossil Plants: Case Studies Documenting the Effects of Air In-Leakage on Steam Plant Operations", presented at the EPRI Condenser Technology Seminar, EPRI, Palo Alto, CA: September 2002. 1004116.
9. D. W. Reynolds, Dynegy Midwest Generation, Personal Communication to A. Aschoff, April 2002.
10. La Porte and R. E. Putman, "The Practical Application of SF_6 and Helium for Condenser Tube and Air In-leakage Detection". Proceedings of the 19th Annual Electric Utility Chemistry Workshop, University of Illinois, May 11-13, 1999.
11. J. W. Harpster, "An Overview of a Comprehensive Study of Condenser Shell Side Dynamics", EPRI Seminar, San Antonio, TX, Sept. 10–12, 2002.
12. J. W. Harpster, "On a Predictive Condenser Performance Model", Condenser Technology Conference, EPRI, Palo Alto, CA: 2005. 1010322.



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3420 Hillview Avenue, Palo Alto, California 94304-1395 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com