

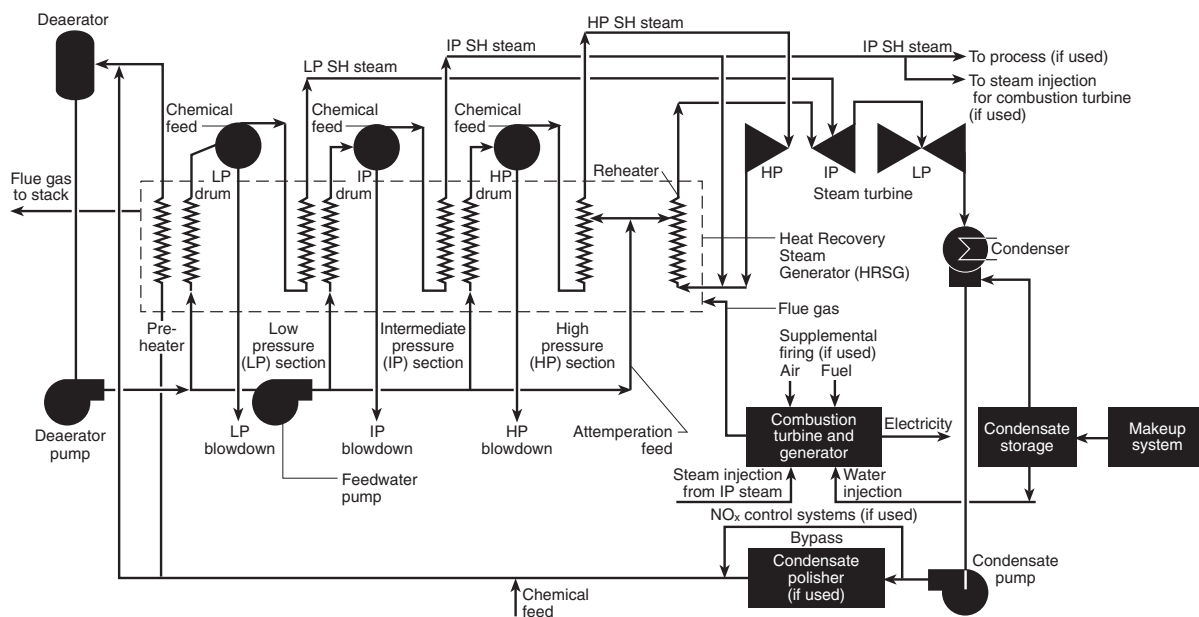
Delivering High Reliability Heat Recovery Steam Generators



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Technical Report



Delivering High Reliability HRSGs

1004240

Final Report, March 2003

EPRI Project Manager
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PRODUCT DESCRIPTION

The worldwide fleet of combined cycle units with heat recovery steam generators (HRSG), despite being relatively new, has exhibited a disappointing track record with respect to reliability and availability in terms of HRSG Tube Failures (HTF). This report identifies actions, which—if implemented prior to commercial operation—should greatly improve the operational HRSG reliability.

Results & Findings

When contemplating new combined cycle units, the potential choices that can adversely impact HRSG reliability are numerous. They may be associated with the original customer specification, the engineering/design, the procurement, fabrication and erection of the unit, commissioning activities, and unit operating and maintenance practices that are often defined prior to commercial operation of the unit. Each phase of the process has been assessed in detail and actions have been established that—if properly implemented—serve to minimize or eliminate future operational reliability issues related to each HRSG tube failure defined in EPRI's *Heat Recovery Steam Generator Tube Failure Manual* (Technical Report 1004503).

Challenges & Objectives

Competition in the power generation industry dictates that capital investments for new generating capacity are minimized to ensure that the project financing can be secured. However, it is equally important to the owner/operator that the unit be capable of high availability and reliability to recover the original capital investment in a timely manner. As a result, a careful balance must be made to ensure that the desired reliability characteristics are inherent in the unit design. Unfortunately, there have been many examples of operating units where low HRSG availability and tube damage has been the direct result of improper assessments during the procurement and commissioning phases.

Applications, Values & Use

Organizations that apply the approaches and good practices presented can develop new combined cycle units with much greater confidence that the expected levels of HRSG reliability will be attained. Follow-up work is planned to demonstrate the commissioning practices described that are needed to avoid HRSG damage and tube failures, particularly those attributed to either improper cycle chemistry or excessive thermal stresses.

EPRI Perspective

In recognition of problems in HRSGs, EPRI initiated research, resulting in establishment of the HRSG Dependability Program, which addresses all aspects of HRSG design and operation. The *Heat Recovery Steam Generator Tube Failure Manual* (Technical Report 1004503) identified the known and future tube damage mechanisms, and established a rationale by which the

mechanism may be determined and the underlying root causes identified and corrected. EPRI has also published a set of cycle chemistry guidelines for HRSGs in the Technical Report *Interim Cycle Chemistry Guidelines for Combined Cycle Heat Recovery Steam Generators (HRSGs)* (TR-110051). Together with the current document, this suite of HRSG guidelines will ensure that HTF are minimized by good design and commissioning, as well as during operation. Future products for HRSGs will include guidelines on chemical cleaning, NDE, and Welding and Repair.

Approach

This report represents the most extensive and comprehensive analysis of HRSG procurement and commissioning practices as it relates to future tube damage and failures. This understanding was attained through the efforts of a team of industry specialists and the support of combined cycle unit equipment manufacturers, constructors, and operators around the world.

Keywords

Heat Recovery Steam Generator (HRSG)
Combined Cycle Units, Reliability
Availability, Tube Failures
Specifications, Design
Construction
Commissioning

ABSTRACT

Modern heat recovery steam generators (HRSGs) have become remarkably complex as designs continue to seek improved efficiencies through higher pressures and temperatures, placing increasing demands on the integrity of the HRSG pressure parts. The potential damage mechanisms that can occur and their remediation have been documented in EPRI's *Heat Recovery Steam Generator Tube Failure Manual*.

The focus of this companion document is the pre-operational **anticipation** of damage in the earliest stages of the life cycle of the HRSG unit, and the institution of design features, construction practices, and commissioning activities that will prevent the accumulation of damage **from the beginning** and thus avoid more expensive post-damage corrective actions.

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1

INTRODUCTION

1.1 Background

Modern heat recovery steam generators (HRSGs) have become remarkably complex, incorporating design features such as multi-pressure circuits, reheat, once-through systems, and combined drum/once-through systems. Designs continue to seek highest efficiencies through higher pressures and temperatures. Pushing the design envelope places increasingly higher demands on the integrity of the HRSG pressure parts.

Damage has occurred in the pressure parts of relatively young HRSG units, often by the same failure mechanisms that have long affected conventional boilers. Realizing that the lessons learned from conventional units might offer significant guidance to addressing the damage in HRSG units, lead to the publication of *Heat Recovery Steam Generator Tube Failure Manual* [1-1]. The focus of that document was on the analysis and subsequent remediation of detected damage in HRSG pressure parts, particularly tubing, resulting from a variety of damage mechanisms (Figure 1-1).

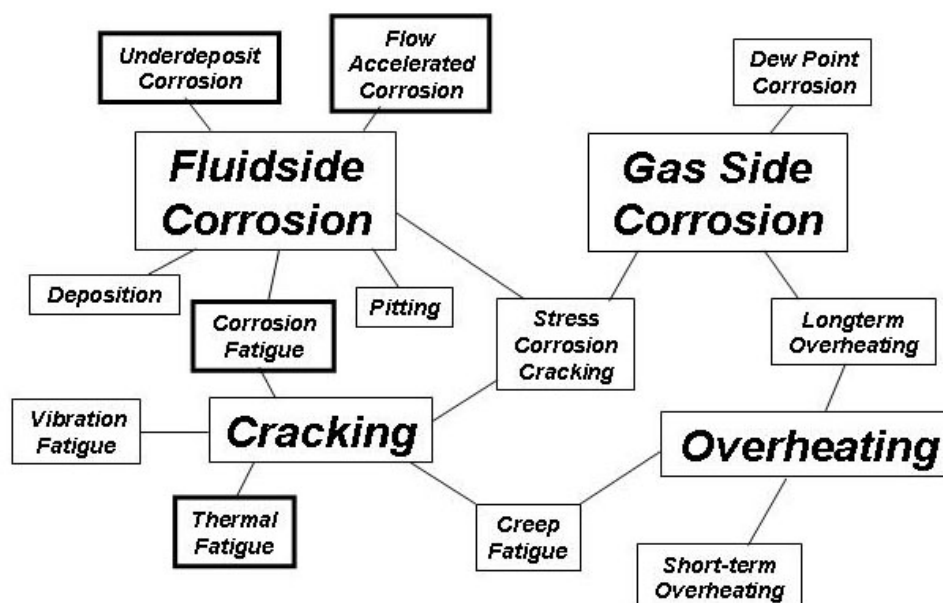


Figure 1-1
HRSG tube damage and failure mechanisms.

Introduction

Because of the nature of the HRSG design, it is often quite expensive to execute any necessary corrective changes to pressure parts after construction is completed. As a result, it was clear that there was an opportunity to anticipate damage accumulation in the earliest stages of the life cycle of the HRSG unit, and to institute design features, construction practices, and commissioning activities that would prevent the accumulation of damage from the beginning and thus attempt to avoid more expensive post-damage fixes. That is the motivation for this companion document.

1.2 Objectives of this Document

The life cycle stages of the HRSG, i.e., owner specification, engineering/design, procurement, fabrication/construction, commissioning, operation and maintenance, are shown schematically in Figure 1-2. A methodology for dealing with HRSG pressure part failures throughout these stages has been developed; that methodology is shown in Figure 1-3. Path A, the subject of this manual, shows stages in the unit life at which actions can be implemented to avoid failures. Paths B and C, the subjects of the *Heat Recovery Steam Generator Tube Failure Manual* [1-1], detail actions to be taken if, in spite of preventative measures, damage or failures have occurred.

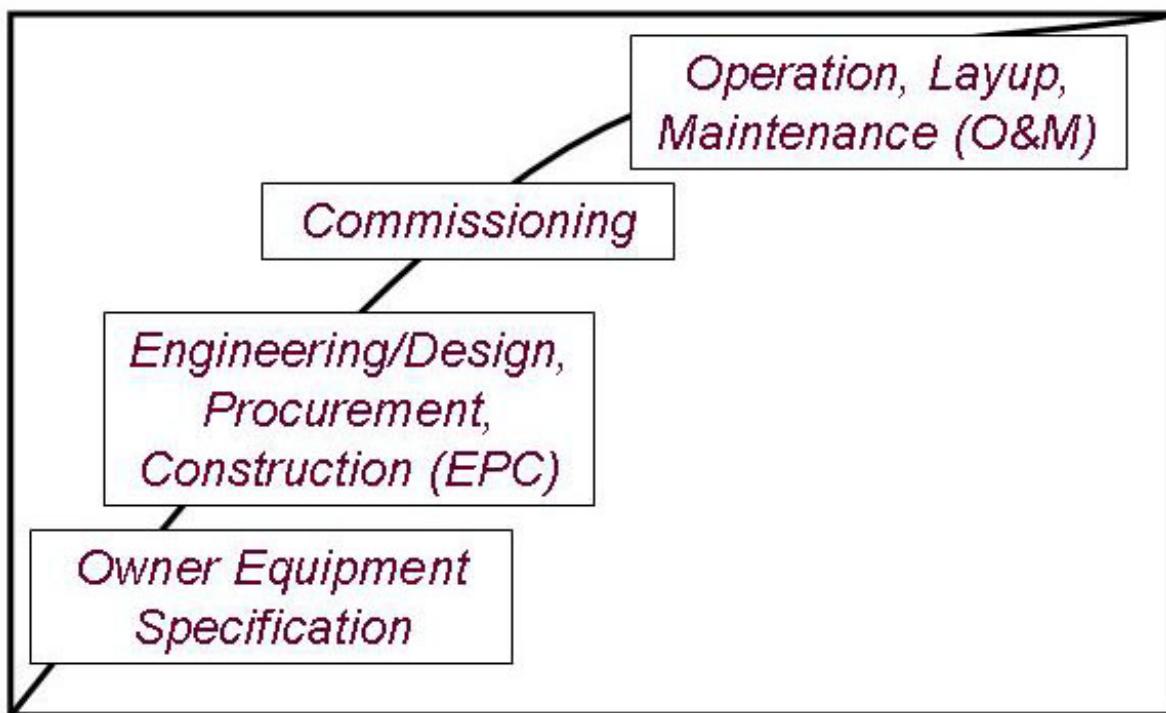


Figure 1-2
The Life Cycle of HRSGs.

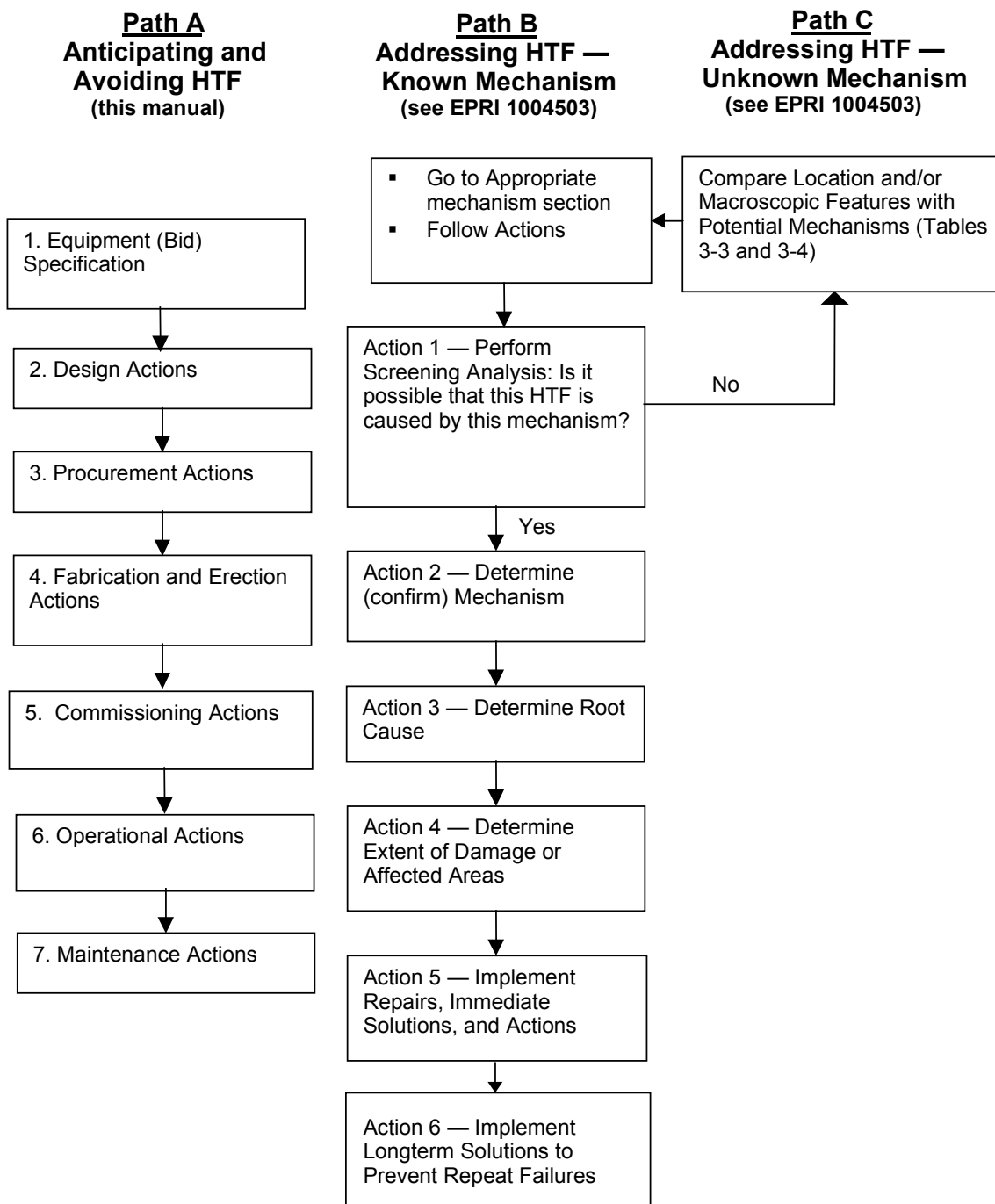


Figure 1-3
Roadmap of actions for dealing with HRSG failures.

The overall objective of this volume is to provide information and recommended actions to be taken during the **initial life cycle stages** of the HRSG (i.e., the stages up to and including commissioning) to avoid conditions that would otherwise lead to eventual HRSG pressure part failures. Post-commissioning issues of operations and maintenance (O&M) issues are not specifically addressed in this volume.

Introduction

The focus of this manual is quite specific. That is, the chapters on design are not intended to address all aspects of HRSG design (a subject which would fill a considerable number of volumes), but are focused quite specifically on key actions to prevent the accumulation of damage in HRSGs. Furthermore, the intent was not to provide a recitation of routine information, so that much common and standard practice information has not been included, leaving the focus on activities that are specific to pressure part damage. A similar philosophy has been employed in addressing procurement specification, fabrication/construction, and commissioning life cycle stages. The particular emphasis is on tubing, with some comments pertaining to thick section headers. Some key actions are summarized schematically in Figure 1-4.

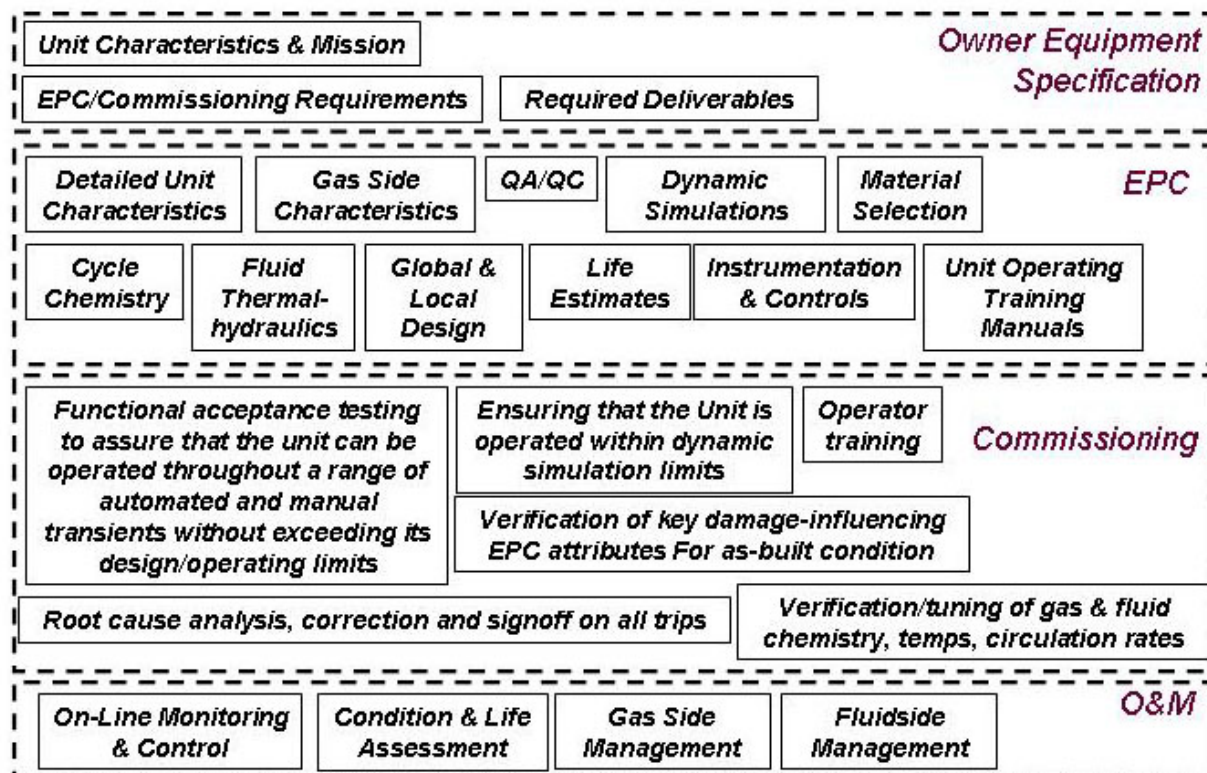


Figure 1-4

Tube failure avoidance actions throughout the life of the HRSG.

1.3 Organization of the Manual

The following topics are covered in this manual:

- Chapter 2 – “Key Damage Avoidance Actions” overviews key avoidance actions. There is considerable detail in the subsequent chapters; this overview is intended to help guide the user to highest priority activities.
- Chapter 3 – “Damage Avoidance by Mechanism” looks at failure avoidance activities organized by mechanism. This chapter is a bit different in format from the others in this manual; it integrates much of the information provided in [1-1]. By presenting avoidance

activities for each HRSG life phase, it sets up the discussion of more detailed information in subsequent chapters.

Chapters 4-8 look at the design phase of the HRSG life cycle:

- Chapter 4 – “Design: Unit Characteristics” includes discussion of overall unit considerations and how choices in overall unit design will influence the potential for later damage. Topics include: (i) operating flexibility, (ii) designing detailed startup, shutdown, and operating procedures, (iii) horizontal and vertical gas path HRSG designs, (iv) gas turbine exhaust influences, and (v) design for maintenance activities.
- Chapter 5 – “Design: Fluid Side” looks primarily at cycle chemistry issues and their key role in avoiding HRSG damage. The full range of cycle chemistry topics is covered including: (i) HRSG hardware choices that will influence the type of chemistry, (ii) optimum feedwater (or pre-HRSG/pre-deaerator) treatment, (iii) optimum HRSG treatment, (iv) setting targets and action levels, (v) ancillary design features, and (vi) an overview of how cycle chemistry choices will impact the development of particular damage mechanisms.
- Chapter 6 – “Design: Gas Side” examines the influence of gas side temperature and environmental effects of various designs. It includes discussion of (i) fuel characteristics and firing systems, (ii) gas flows and temperatures, (iii) gas side condensate management, and (iv) emissions influences.
- Chapter 7 – “Design: Stresses” includes a very detailed look at subtle effects of thermally induced stresses; it also examines the influence of connection design, supports, avoidance of the resulting stress concentrations, and other contributions to potentially damaging stresses in tubing and headers. Design of venting and drain systems, as means to alleviate development of specific stresses, is also included.
- Chapter 8 – “Design: Instrumentation and Controls” looks at (i) cycle chemistry monitoring, (ii) chemical feed systems and controls, and (iii) sequence and modulating controls.
- Chapters 9 and 10 look at two other life cycle phases – Fabrication/Construction (Chapter 9) and Commissioning (Chapter 10).
- Appendix A – Examples of detailed operating procedures for startups and shutdowns are provided in Appendix A.

1.4 Format of Chapters 4-10

Chapters 4-10 are organized in a consistent format and, where appropriate, key actions have been identified. These are placed at the beginning of a major section or subsection. Along with each action is an explanation of why the action is important (“Rationale”), and what key damage types the action will help to avoid (“Potential HRSG Damage”). A sample shows the format:

Action 6.2c During design of the supplemental firing system and export/extraction steam flows, include measures to avoid locally high temperatures in the HRSG.

Rationale: Temperatures in excess of nominal expected design can be a major contributor to a number of HRSG tube failure mechanisms.

Potential HRSG Damage: Short term overheating, increased evaporator tube deposition, increased potential for underdeposit corrosion mechanisms, and increased flow-accelerated corrosion due to increased flows.

The action, rationale and potential damage summary statements are then followed by text that expands on the discussion and typically provides details of how to implement the required action.

Note that the actions are numbered according to the section of text in which they are contained and discussed. If more than one action is contained in each section, they are identified by a letter as Action 6.2a, Action 6.2b, etc.

With the exception of the summary provided by mechanism in Chapter 3, this manual does not specifically address the operating stage of the HRSG, nor does it provide detailed maintenance instructions. Clearly, continuing the good practices that have been established through the commissioning phase will be critical to avoiding pressure part damage during operation. The general philosophy of good practice during operation is discussed throughout this document, but detailed operating and maintenance procedures will be comprehensive and unit-specific, and as a result are not addressed here.

1.5 Accessing the Information in this Document

Two quick indices to the information contained in this document are provided. Chapter 2 provides an index to the information organized by general subject. Table 2-1 of that chapter also includes a comprehensive list of all actions delineated in the report, the rationale behind each action, the damage types that are affected, and provides a report section number for more information.

Chapter 3 is organized by damage type. The reader interested in specific actions to avoid a specific damage type can start in that chapter and will find a comprehensive list of actions, plus direction to material throughout the report to support the search for relevant information.

1.6 References

[1-1]. Dooley, R.B., K.J. Shields, S.R. Paterson, T.A. Kuntz, W.P. McNaughton, and M. Pearson, *Heat Recovery Steam Generator Tube Failure Manual*, 1004503, EPRI, Palo Alto, CA., 2002.

2

KEY FAILURE AVOIDANCE ACTIONS

2.1 Introduction and Use of This Chapter

This chapter provides an index to the material contained in the balance of the report (with the exception of Chapter 3). The information presented here is organized by general subject, as follows:

- I. Cyclic unit operation
- II. Gas flows and temperatures
- III. Design allowance for maintenance
- IV. Cycle chemistry
 - A. Early design decision
 - B. Choice of treatments
 - C. Impurity targets and action levels
 - D. Ancillary design features
 - E. Cycle chemistry monitoring (see XII. Instrumentation and controls)
- V. Chemical cleaning
- VI. Fuels
- VII. Supplemental firing
- VIII. Gas side condensate management
- IX. HRSG issues related to emissions control
- X. Stresses
 - A. General
 - B. Headers
 - C. Tube-to-header attachments
 - D. SH and RH drains
 - E. Attemperators
 - F. Evaporators
 - G. Economizers and preheaters
- XI. Connections and attachments
- XII. Instrumentation and controls
- XIII. Supports
- XIV. Noise/vibration
- XV. Transport and storage

Column 1 of Table 2-1 provides the general subject. The second column indicates the recommended action. A couple of key words are indicated in bold in each action to further indicate the topic being discussed. The rationale behind each recommendation, and the types of HRSG pressure damage that the action aims to avoid are listed in Columns 3 and 4.

Key Failure Avoidance Actions

The final column indicates two things. First, it provides an index to where in the report that more information may be found about this topic. Secondly, it indicates a critical factor in avoiding HRSG damage. That is, the actions need to be executed throughout the life cycle of the unit. It is not sufficient to design-in appropriate practices. Those practices need to be built-in during fabrication/construction, confirmed during commissioning, then monitored through the operation of the unit. The final column of Table 2-1 indicates some of the key follow-through actions that are delineated in this report. The abbreviations Fab/Cons (fabrication/construction) and Comm (Commissioning) are used. As can be seen there, this report has a heavy design-phase emphasis with some overview coverage of fabrication/construction and commissioning.

As with the balance of material in this document, this list is not intended to be comprehensive. It focuses exclusively on design and commissioning activities specifically required to prevent HRSG pressure part damage. Many important design activities and commissioning needs have not been covered here; this does not imply that they are of lesser importance, merely that the items summarized in Table 2-1 and discussed throughout this report have arisen in the specific examination of HRSG pressure part damage prevention.

Table 2-1
Master List of Actions/Topics and Relevant Text Sections
(showing continuity through HRSG life cycle phases)

General Subject	Specific Topic/Action	Rationale	To Avoid These Damage Mechanisms	Life Phase/ (Report Section)
I. Cyclic Unit Operation	Design for cyclic operation of HRSG and key auxiliaries; confirm during commissioning (Actions 4.2a; 10.2a)	Stresses and cycle chemistry changes caused by cycling cause most of damage to HRSG pressure parts.	Essentially all HRSG damage mechanisms are caused or exacerbated by stresses or cycle chemistry.	Design (Sec. 4.2) Comm (Sec. 10.2)
	Specify annual operating transients for the unit. (Action 4.2b)	"	"	Design (Sec. 4.2)
	Develop detailed startup, shutdown, and operating procedures early in the design process; confirm during commissioning that they produce acceptable stresses (Actions 4.3a; 10.2a; 10.2b; 10.3a; 10.8a; 10.8b)	Stresses and cycle chemistry changes caused by various operating procedures cause most of damage to HRSG pressure parts.	"	Design (Sec. 4.3) Comm (Sec. 10.2; Sec. 10.3; 10.8)
	Design appropriate hardware and controls to achieve control needed for optimized operating procedures; confirm during commissioning (Actions 4.3b; 5.10b; 10.2a; 10.5, 10.8a; 10.8b)	"	"	Design (Sec. 4.3; Sec. 5.10.1) Comm (Sec. 10.2; Sec. 10.5; 10.8)
II. Gas Flows and Temperatures	Understand the role of combustion turbine (CT) exhaust gas temperatures on cyclic life of HRSG pressure parts. (Action 4.5a)	High transient stresses during changes in gas temperatures can lead to significant pressure part damage.	Creep fatigue, thermal fatigue, and possibly corrosion fatigue.	Design (Sec. 4.5)
	Specify/ensure that the CT is capable of maintaining a moderate exhaust gas temperature at minimum CT output after synchronizing.; confirm during commissioning (Actions 4b; 10.7; 10.8a; 10.8b)	To limit initial tube-to-header temperature differences.	Creep fatigue, thermal fatigue.	Design (Sec. 4.5) Comm (Sec. 10.7; 10.8)
	Ensure that CT is capable of controlling rate of change of gas temperature during startups and shutdowns to operator- or DCS-selected ramp rates; confirm during commissioning (Actions 4c; 6.5c; 10.5; 10.7; 10.8a; 10.8b)	To match gas temperatures to those developing in HRSG pressure parts and steam turbine during operating transients.	Thermal fatigue, creep fatigue.	Design (Sec. 4.5; Sec. 6.5.3) Comm (Sec. 10.5; Sec. 10.7; 10.8)

Key Failure Avoidance Actions

Table 2-1
Master List of Actions/Topics and Relevant Text Sections (continued)

General Subject	Specific Topic/Action	Rationale	To Avoid These Damage Mechanisms	Life Phase/ (Report Section)
	Design attenuator position to avoid overspraying during on load operation. (Action 4.5d)	To reduce tube-to-tube temperature variations.	Thermal fatigue	Design (Sec. 4.5)
	Pick appropriate rate of change of CT output during on load operation to limit rate of changes in steam temperature. (Action 4.5e)	To reduce thermal stresses in HRSG pressure parts.	Thermal fatigue	Design (Sec. 4.5)
	Specify OEM reports to identify excessive gas flow or gas temperature conditions, especially on units with supplemental firing. (Action 6.3a)	Excessive flue gas temperatures and flow variances have significant potential impact on HRSG pressure parts.	Short term and longterm overheating, underdeposit corrosion mechanisms, economizer steaming, thermal fatigue, deposits	Design (Sec. 6.3)
	Specify techniques to measure flue gas distribution; confirm that distributions are acceptable during commissioning (Actions 6.3b; 10.7; 10.8a; 10.8b)	"	"	Design (Sec. 6.3.1) Comm (Sec. 10.7; 10.8)
	Specify construction of a 3-D physical flow model, supplemented with computational fluid dynamics model, as needed. (Action 6.3c)	"	"	Design (Sec. 6.3.1.1)
III. Design Allowance for Maintenance	Require design features that will allow for appropriate inspections, cleaning and repair access of HRSG pressure parts. (Action 4.6a)	Designing in access will help alleviate future problems in these notoriously difficult access areas.	To aid in the early detection and repair of any damage mechanism.	Design (Sec. 4.6)
IV. Cycle Chemistry				
IV. A. Early design decisions	Need specific design for makeup treatment plant based on characteristics of water supply and needs of the combined cycle unit. (Action 5.3)	Proper makeup systems are integral to the avoidance of corrosion and deposition; also maximizes effectiveness of blowdown and condensate polishers.	All waterside corrosion mechanisms, including underdeposit mechanisms.	Design (Sec. 5.3)

Table 2-1
Master List of Actions/Topics and Relevant Text Sections (continued)

General Subject	Specific Topic/Action	Rationale	To Avoid These Damage Mechanisms	Life Phase/ (Report Section)
IV. A. Early design decisions (cont.)	Specify that all materials in the feedwater system are all-ferrous. (Action 5.4)	All-ferrous designs can use preferred water treatment approaches; better unit availability, reliability and performance are expected with all-ferrous systems.	Waterside deposition and underdeposit corrosion mechanisms.	Design (Sec. 5.4)
	Specify, if at all possible, a condensate polisher. (Action 5.5a)	Contamination from water cooled condensers is the root cause of numerous damage types. Optimal designs will therefore include polishers and/or "leak-tight" titanium condenser tubes.	Waterside deposition, corrosion and cracking mechanisms.	Design (Sec. 5.5)
	If a condenser is to be used, ensure that it is designed to be "leak-tight" and constructed of titanium tubes for best chemistry performance. (Action 5.5.b)	"	"	Design (Sec. 5.5)
	Consider the impact of design features such as (i) forward feeds of LP drum water to the IP and HP, or (ii) IP drum to the HP circuit, or (iii) cascading of evaporator blowdown to lower pressure circuits. (Action 5.6b)	Potential for steam purity problems if the impact of these design features are not considered	Unit specific, possible deposition and corrosion problems in evaporator and superheater.	Design (Sec. 5.6.2)
	Select dissolved oxygen levels consistent with feedwater chemistry most suitable for monitoring and maintaining at target levels during all operating modes; confirm during commissioning (Actions 5.6c; 10.6)	Deaeration is important to avoid the introduction of highly oxygenated water into HRSG tubes during startups and normal operation.	Pre-HRSG corrosion activity, deposition in evaporator circuits; increased risks of chemistry-related HTF, more frequent chemical cleaning; pitting corrosion	Design (Sec. 5.6.3) Comm (Sec. 10.6)

Key Failure Avoidance Actions

Table 2-1
Master List of Actions/Topics and Relevant Text Sections (continued)

General Subject	Specific Topic/Action	Rationale	To Avoid These Damage Mechanisms	Life Phase/ (Report Section)
	Design how deaeration will be accomplished, both within the cycle and for treated makeup water; confirm during commissioning (Actions 5.6d; 10.6)	"	"	Design (Sec. 5.6.3) Comm (Sec. 10.6)
	Ensure means to monitor condenser air removal rates in real time.; confirm during commissioning (Action 5.10c; 10.6)	Excessive air in-leakage introduces dissolved oxygen, CO ₂ , dust and debris into the cycle. Control of air ingress is essential for effective chemistry control.	Increased corrosion of carbon steel components with subsequent transport of iron oxides to evaporators where deposits are formed.	Design (Sec. 5.10.2) Comm (Sec. 10.6)
	Assess probable impacts of attenuation on steam purity. (Action 5.6e)	To protect steam tubing and the turbine from damage.	Deposition and corrosion in superheaters and reheaters.	Design (Sec. 5.6.4)
IV. B. Choice of treatments	Select initial chemistry for feedwater (or pre-HRSG or pre-Deaerator) treatment, then verify and optimize the treatments during commissioning. (Actions 5.6a; 5.7a; 10.6)	To minimize the generation and transport of iron oxides into the HRSG and turbine; to prevent corrosion of pre-HRSG cycle components.	HRSG tube failures; failure of piping and tubing within the feedwater system due to FAC; feedpump fouling, HRSG deposits; underdeposit corrosion mechanisms.	Design (Sec. 5.6.1; Sec. 5.7) Comm (Sec. 10.6)
	Ensure that, for all-ferrous systems, the feedwater treatment must be either all-volatile treatment, specifically AVT (O) or oxygenated treatment. (Action 5.7b)	"	"	Design (Sec. 5.7)
	Consider the materials of any feedwater heater or preheater circuits as part of the feedwater treatment selection process. (Action 5.6f)	Differences in feedwater heater or preheater materials may influence how the treatment is selected and optimized.	Deposit-related mechanisms such as underdeposit corrosion and overheating; corrosion within feedwater heater and/or preheater.	Design (Sec. 5.6.5)

Table 2-1
Master List of Actions/Topics and Relevant Text Sections (continued)

General Subject	Specific Topic/Action	Rationale	To Avoid These Damage Mechanisms	Life Phase/ (Report Section)
	Determine suitable evaporator treatment during design to allow verification and refinement during the commissioning period. (Actions 5.8; 10.6)	Most early HTF are related to improper HRSG treatment.	A variety of chemistry-related HTF – of particular concern is flow-accelerated corrosion.	Design (Sec. 5.8) Comm (Sec. 10.6)
IV. C. Impurity targets and action levels	Establish customized limits for chemistry parameters such as sodium, silica, cation conductivity and organics based on EPRI guidelines; confirm appropriateness of choices during commissioning (Actions 5.9; 10.6)	Need to establish limits that should not lead to corrosion or deposition problems.	A variety of corrosion and deposition problems, particularly in the evaporator sections of the HRSG and the turbine.	Design (Sec. 5.9) Comm (Sec. 10.6)
IV. D. Ancillary design features	Develop appropriate layup procedures. (Action 5.10a)	The incursion of oxygen during unit shutdown can cause damage through the HRG by increasing corrosion and initiating pitting/corrosion damage.	All cycle chemistry induced mechanisms including deposits, underdeposit corrosion mechanisms, pitting, stress corrosion cracking, and corrosion fatigue.	Design (Sec 5.10.1)
	Design facilities needed to execute proper unit shutdown and layup; confirm efficacy during commissioning (Actions 4.3b; 5.10b; 10.6)	"	"	Design (Sec 4.3; Sec. 5.10.1) Comm (Sec. 10.6)
IV. E. Cycle Chemistry Monitoring (see under XII. Instrumentation and Controls)				

Key Failure Avoidance Actions

Table 2-1
Master List of Actions/Topics and Relevant Text Sections (continued)

General Subject	Specific Topic/Action	Rationale	To Avoid These Damage Mechanisms	Life Phase/ (Report Section)
V. Chemical Cleaning	Require design features that will allow for adequate chemical cleaning. (Action 4.6b)	Proper chemical cleaning, particularly rinsing of all cleaned surfaces is critical to avoid damage to pressure parts.	Underdeposit corrosion mechanisms, generalized corrosion.	Design (Sec. 4.6)
	Ensure design features to optimize chemical cleaning such as permanent chemical cleaning piping and valves, or access for installation of temporary piping and valves. (Action 5.10d)	Need a means to safely introduce and remove cleaning solutions to equipment.	Mechanisms that require deposits to be present such as underdeposit corrosion mechanisms, overheating, etc.	Design (Sec. 5.10.3)
	Establish and execute appropriate cleaning procedures to ensure clean and passive surfaces of HRSG components prior to unit startup. (Action 9.5a)	Prevent accumulation of contaminants in the cycle; prevent corrosion of pressure part surfaces; prevent accumulation of debris in pressure parts.	Corrosion processes; deposition, short term overheating from blockages.	Fab/Cons (Sec. 9.5)
	Prior to initial operation, the water surfaces of the steam generator should be evaluated and cleaned by physical and/or chemical processes (Action 9.5b)	"	"	Fab/Cons (Sec. 9.5)
	Prior to initial operations, procedures such as steam or air blowing should be completed to remove loose particles and foreign objects from steam tubing and piping. (Action 9.5c)	"	"	Fab/Cons (Sec. 9.5)

Table 2-1
Master List of Actions/Topics and Relevant Text Sections (continued)

General Subject	Specific Topic/Action	Rationale	To Avoid These Damage Mechanisms	Life Phase/ (Report Section)
VI. Fuels	Evaluate potential fuels for the effects on HTSG pressure parts. (Action 6.2a)	Firing fuels that contain sulfur will affect the protective oxide layer that forms on pressure parts.	Gas side corrosion, acid dewpoint corrosion, stress corrosion cracking; increases in fouling for oil firing.	Design (Sec. 6.2.2)
	Determine likelihood for firing fuels containing more than minimum levels of sulfur. (Action 6.2b)	"	"	Design (Sec. 6.2.2)
VII. Supplemental Firing	During design of the supplemental firing system and export/extraction steam flows, include measures to avoid locally high temperatures in the HRSG.; confirm during commissioning (Actions 6.2c; 10.7; 10.8a; 10.8b)	Excessive temperatures can lead to a variety of HTF.	Short term overheating, evaporator tube deposits, underdeposit corrosion mechanisms, flow-accelerated corrosion.	Design (Sec. 6.2.4) Comm (Sec. 10.7; 10.8)
VIII. Gas Side Condensate Management	Incorporate design practices to minimize or eliminate condensation during operation; evaluate their effectiveness during commissioning (Actions 6.4a; 10.7; 10.8a; 10.8b)	Condensation increases fouling, increases back pressure, and changes pressure part temperatures and heat transfer; also may be corrosive.	Gas side pitting and corrosion, acid dewpoint corrosion and stress corrosion cracking.	Design (Sec. 6.4) Comm (Sec. 10.7; 10.8)
	Evaluate whether cold end temperatures, expected level of contaminants and alloy choice are likely to result in significant deposition and corrosion. (Action 6.4b)	If operating conditions in the economizer or water heater tubes falls below the acid dewpoint, corrosion could occur.	Acid dewpoint corrosion.	Design (Sec. 6.4.1)
	Determine the appropriate corrosion allowances or methods for mitigating that corrosion. (Action 6.4c)	"	"	Design (Sec. 6.4.1)
	Ensure that proper material choices are made for low temperature sections. (Action 6.4d).	"	"	Design (Sec. 6.4.1)

Key Failure Avoidance Actions

Table 2-1
Master List of Actions/Topics and Relevant Text Sections (continued)

General Subject	Specific Topic/Action	Rationale	To Avoid These Damage Mechanisms	Life Phase/ (Report Section)
	Ensure that the water source for aqueous ammonia reagent use in SCR's does not contain chloride salts or chlorine for HRSG constructed with austenitic stainless steels. (Action 6.4e)	Potential for stress corrosion cracking with these conditions.	Stress corrosion cracking	Design (Sec. 6.4.2)
	Take care in specifying fin spacing if fuel oils are like to see significant use. (Action 6.4f)	External deposits (fouling) of tube surfaces will affect heat transfer; cleaning may be difficult and costly.	Fouling	Design (Sec. 6.4.3)
IX. HRSG Issues Related to Emissions Control	Determine purity requirements for water or steam used to reduce NO_x levels. (Action 6.5a).	Water injection for NO _x control can carry contaminants into the HRSG.	Gas side corrosion and pitting.	Design (Sec. 6.5.1)
	Evaluate methods for minimizing ammonium sulfate formation. (Action 6.5b)	Sulfur from fuel can combine with unreacted ammonia from SCR to form ammonium sulfates and lead to fouling and potential corrosion of HRSG tubes.	Gas side fouling and corrosion.	Design (Sec. 6.5.2)
X. Stresses				
X. A. General	Identify and evaluate the potential sources and enhancers of thermally-induced stresses in HRSG circuits and apply the appropriate design features to mitigate them; confirm during the commissioning process (Actions 7.2; 10.2e; 10.3b; 10.8a; 10.8b)	To prevent excessive transient and steady-state thermal stresses in HRSG pressure parts.	Primarily thermal fatigue, creep fatigue, and corrosion fatigue.	Design (Sec. 7.2) Comm (Sec. 10.2; Sec. 10.3; 10.8)
	Understand that the common international steam generator codes may not provide adequate guidance for some key design issues; require suppliers to provide design basis for critical calculations. (Action 7.3)	Prevention of failures will require use of guidance from international codes plus sophisticated analytical modeling to prevent damage.	Thermal fatigue, creep fatigue, and corrosion fatigue.	Design (Sec. 7.3)

Table 2-1
Master List of Actions/Topics and Relevant Text Sections (continued)

General Subject	Specific Topic/Action	Rationale	To Avoid These Damage Mechanisms	Life Phase/ (Report Section)
	Be aware that significant thermally induced stresses can develop during commissioning testing itself and care needs to be taken to understand and avoid the most damaging transients (Action 10.2c; 10.8a; 10.8b)	Prevent accumulation of damage as a result of the commissioning testing.	Primarily creep fatigue and thermal fatigue.	Comm (Sec. 10.2; 10.8)
X. B. Headers	Minimize header thickness and diameter through choice of materials. (Action 7.4a)	Will increase the response of the header to thermal changes, and decrease thermal stresses.	Thermal fatigue or creep fatigue.	Design (Sec. 7.4)
	Search for means to reduce large thermal shocks to headers; confirm during commissioning tests (Actions 7.4b; 10.3a/b; 10.8a; 10.8b)	Will decrease thermal stresses.	Thermal fatigue or creep fatigue.	Design (Sec. 7.4) Comm (Sec. 10.3; 10.8)
	Install means to prevent shocking of hot LP economizer/preheater inlet headers by cold feedwater during startups.; confirm during commissioning testing (Actions 7.4c; 10.3b)	Will lower thermal stresses and increase header life.	Thermal fatigue in headers; corrosion fatigue and thermal fatigue in tubes at attachment welds.	Design (Sec. 7.4.2) Comm (Sec. 10.3; 10.8)
X. C. Tube-to-Header Attachments	Utilize panel designs with a single row of straight tubes attached radially to the same pair of upper and lower headers. (Actions 7.5a; 7.8a)	Will reduce temperature differences between tubes, thus lowering stresses at attachment welds.	Thermal fatigue, creep fatigue, and corrosion fatigue.	Design (Sec. 7.5; Sec. 7.8)
	For panel designs with two tube rows, perform stress analysis and cyclic life calculations; confirm with commissioning testing (Actions 7.5b; 7.8b; 10.3b)	To ensure that adequate cyclic life is designed into panel construction.	Thermal fatigue, creep fatigue and corrosion fatigue.	Design (Sec. 7.5; Sec. 7.8) Comm (Sec. 10.3)
	For panel supports in HGP HRSGs, where possible, ensure that load transfer does not occur between different supports on heating and cooling; if load transfer between supports will occur, confirm that an acceptable design life will result; confirm during commissioning (Actions 7.6a; 10.3b; 10.8a; 10.8b)	Global temperature differences applied to tubes and interconnecting pipes between panels can result in high stresses.	Creep fatigue, thermal fatigue or corrosion fatigue around tube attachments to welds.	Design (Sec. 7.6) Comm (Sec. 10.3; 10.8)

Key Failure Avoidance Actions

Table 2-1
Master List of Actions/Topics and Relevant Text Sections (continued)

General Subject	Specific Topic/Action	Rationale	To Avoid These Damage Mechanisms	Life Phase/ (Report Section)
	Ensure that supports for horizontal tubes in VGP HRSGs allow for tubes to slide axially during expansion and contraction; confirm during commissioning (Actions 7.6b; 10.3b; 10.8a; 10.8b)	"	"	Design (Sec. 7.6) Comm (Sec. 10.3; 10.8)
X. D. SH and RH Drains	Ensure adequate SH and RH drain systems incorporating appropriate design features; confirm during commissioning (Actions 7.7a; 10.4; 10.8a; 10.8b)	If condensate cannot be drained, the result will be high tube-to-tube temperature differences and thermal shock at tube holes and inner surfaces of headers.	Thermal fatigue, corrosion fatigue, or thermal quench overload; water induction to the turbine.	Design (Sec. 7.7) Comm (Sec. 10.4; 10.8)
	Establish appropriate operating procedures for clearing condensate, particularly on unit startup; confirm the efficacy during commissioning testing (Action 7.7b; 10.3a/b; 10.4; 10.8a; 10.8b)	"	"	Design (Sec. 7.7) Comm (Sec. 10.3; 10.8)
X. E. Attemperators	Ensure attemperators are properly positioned; confirm during commissioning (Actions 7.9a; 10.3b; 10.8a; 10.8b)	To prevent the admission of unmixed or unflashed attemperation water into downstream SH/RH headers resulting in thermal stresses.	Overheating, creep fatigue, thermal fatigue, corrosion fatigue, ductile overload.	Design (Sec. 7.9) Comm (Sec. 10.3; 10.8)
	Ensure design details to allow complete mixing and flashing of all spray water from attemperators before the first downstream pipe branch. (Action 7.9b)	"	"	Design (Sec. 7.9)
	Prevent leakage of water past spray control valves by appropriate layout of attemperator and pipes. (Action 7.9c)	"	"	Design (Sec. 7.9)
X. F. Evaporators	Verify by analysis and measurement the cyclic design life of evaporator downcomer, interconnecting pipes, headers, tubes, and risers; confirm during commissioning (Actions 7.10; 10.3b; 10.8a; 10.8b)	Evaporators can develop significant transient thermal stresses between successive tube rows and downcomers during startups.	Thermal fatigue in tubes, pipes, and downcomers.	Design (Sec. 7.10) Comm (Sec. 10.3; 10.8)

Table 2-1
Master List of Actions/Topics and Relevant Text Sections (continued)

General Subject	Specific Topic/Action	Rationale	To Avoid These Damage Mechanisms	Life Phase/ (Report Section)
X. G. Economizers and Preheaters	Economizers should be designed for all air and any vapor formed during startups or load reductions is immediately vented; confirm during commissioning (Actions 7.11a; 10.4; 10.8a; 10.8b)	Tube temperature differences in economizers caused by deficient venting are a source of significant thermal stress.	Thermal fatigue, increased deposition and corrosion, flow-accelerated corrosion.	Design (Sec. 7.11.1) Comm (Sec. 10.4; 10.8)
	Venting or equivalent should be designed in economizers to control thermal stresses produced during steaming; confirm during commissioning (Actions 7.11b; 10.4; 10.8a; 10.8b)	"	"	Design (Sec. 7.11.1) Comm (Sec. 10.4; 10.8)
	Locate the LP and IP feedwater control valves between the outlet of the respective preheater/economizer and steam drum, and design feedwater pumps to operate at a pressure significantly higher than their respective drum operating pressures. (Action 7.11c)	Elevates the saturation temperature in economizer tubes, thereby reducing the extent of steaming in the economizers.	"	Design (Sec. 7.11.2)
	Locate the IP superheater section between the HP evaporator and final HP economizer sections, and the LP superheater between the IP and the IP economizer sections. (Action 7.11d)	The small IP and LP superheater sections lower the gas temperature entering the downstream economizer sections, which minimizes the risk of steaming the economizers.	"	Design (Sec. 7.11.2)
	Ensure that effective baffles are provided between tubes and duct side wall and between adjacent tube modules. (Action 7.11f)	Minimizes the risk of steaming the preheater and economizers.	"	Design (Sec. 7.11.2)
	In new construction for cycling service, use alternatives to hairpin tube type economizers and preheaters. (Action 7.11g)	Large forces on supports of hairpin tube type economizers can lead to tube attachment damage.	"	Design (Sec. 7.11.2)

Key Failure Avoidance Actions

Table 2-1
Master List of Actions/Topics and Relevant Text Sections (continued)

General Subject	Specific Topic/Action	Rationale	To Avoid These Damage Mechanisms	Life Phase/ (Report Section)
X. G. Economizers and Preheaters (cont.)	On existing installations, modify the supports on the inlet or outlet headers of hairpin tube economizers to incorporate springs. (Action 7.11h)	"	"	Design (Sec. 7.11.2)
	Design economizer headers so that tubes of separate sections can expand independently when large temperature differences occur transiently during startups; confirm during commissioning (Actions 7.12; 10.3b; 10.8a; 10.8b)	To avoid thermally-induced stresses in tubes of different sections during transients.	Thermal fatigue, corrosion fatigue	Design (Sec. 7.12) Comm (Sec. 10.3; 10.8)
	Design economizer panels to minimize thermal stress caused by differential cooling of heated economizer tubes on startups; confirm during commissioning (Actions 7.13; 10.3b; 10.8a; 10.8b)	To avoid high transient thermal stresses.	Thermal fatigue, corrosion fatigue	Design (Sec. 7.13) Comm (Sec. 10.3; 10.8)
	Include means to prevent buoyancy effects in economizers/preheaters.	To reduce high transient stresses.	Thermal fatigue, corrosion fatigue	Design (Sec. 7.14)
	Prevent leakage past isolating valves of lower header drains of economizers/preheaters to the lower headers to higher temperature sections by separately double isolating and not interconnecting drains. (Action 7.15a)	To prevent large tube-to-tube temperature differences.	Thermal fatigue, corrosion fatigue	Design (Sec. 7.15)
	Ensure all sections in the HRSG have no low points that cannot be completely drained by gravity; confirm during commissioning (Actions 7.15b; 10.4)	To prevent freeze damage.	Freeze damage	Design (Sec. 7.15) Comm (Sec. 10.4)

Table 2-1
Master List of Actions/Topics and Relevant Text Sections (continued)

General Subject	Specific Topic/Action	Rationale	To Avoid These Damage Mechanisms	Life Phase/ (Report Section)
XI. Connections and Attachments	Understand the relative merits and limitations of alternative tube-to-header attachments. Specify geometries to achieve required cycling service. (Action 7.16a)	Utilization of inappropriate tube-to-header attachments, fabrication and heat treatment, or inadequate inspections increase the risk of tube failures.	Thermal fatigue, creep fatigue, corrosion fatigue	Design (Sec. 7.16)
	Avoid offset tube attachments where possible in designing tube-to-header connections (Action 7.16b)	"	"	Design (Sec. 7.16)
	For tube and header arrangements with the potential for high thermally induced stresses, such as offset tube attachments, perform conservative analysis to determine where superior strength attachments are required. (Action 7.16c)	"	"	Design (Sec. 7.16)
	Ensure that panel fabrication and inspection are appropriate for the type of tube-to-header arrangement used and the extent of cycling service anticipated.	"	"	Design (Sec. 7.16)
	Confirm that bending stresses at tube-to-header attachments applied by pipes to the headers will provide acceptable joint lifetimes. Modify piping if necessary. (Action 7.16e)	To eliminate a significant contributor to tube failures at header attachments.	Creep fatigue, thermal fatigue, corrosion fatigue	Design (Sec. 7.16.2)
	Avoid material transitions between headers and tubes. (Action 7.16f)	To minimize/delay the possibility of Type IV or creep fatigue cracking at P91 welds by reducing axial and radial stresses at the transition welds.	Early Type IV or creep fatigue cracks	Design (Sec. 7.16.3)
	Locate P22 to P91 welds where bending moments and axial stresses in the pipes are low and where the transition welds are accessible for periodic NDE. (Action 7.16g)	"	"	Design (Sec. 7.16.3)

Key Failure Avoidance Actions

Table 2-1
Master List of Actions/Topics and Relevant Text Sections (continued)

General Subject	Specific Topic/Action	Rationale	To Avoid These Damage Mechanisms	Life Phase/ (Report Section)
XI. Connections and Attachments (cont.)	Allow space for, and utilize a P91 transition piece to match pipe thicknesses at, P22/P91 transition welds. (Action 7.16h).	"	"	Design (Sec. 7.16.3)
	The design of transition welds should account for the reduced stress rupture and creep fatigue properties of the weld. (Action 7.16i)	"	"	Design (Sec. 7.16.3)
	Avoid shared headers with internal division plates for cycling service. (Action 7.16j)	Internal division plates may heat and cool at different rates to the header wall on each side and thus develop thermal stresses in the welds.	Thermal fatigue, corrosion fatigue.	Design (Sec. 7.16.4)
	For HRSGs intended for cycling, perform analysis to verify that division plate integrity is compatible with design life. (Action 7.16k)	"	"	Design (Sec. 7.16.4)
	Develop, qualify and carefully perform proper welding and heat treatment when fabricating components using modified 9% Cr materials. (Action 9.4)	Avoidance of weld related problems specific to 9% Cr materials.	Weld-related cracking	Fab/Cons (Sec. 9.4)
XII. Instrumentation and Controls	During design, specify instrumentation and locations for measuring gas flow characteristics; use during commissioning to confirm that actual conditions are within design envelope (Actions 6.3d; 10.7; 10.8a; 10.8b)	Excessive flue gas temperatures and flow variances have significant potential impact on HRSG pressure parts.	Short term and longterm overheating, underdeposit corrosion mechanisms, economizer steaming, thermal fatigue, deposits	Design (Sec. 6.3.1.2) Comm (Sec. 10.7; 10.8)
	Design controls to maintain stable pressures in the HP, IP and LP steam drums, even during major upset incidents; confirm during commissioning (Actions 7.11e; 10.5; 10.8a; 10.8b)	Minimizes the risk of steaming the preheater and economizers.	Thermal fatigue, increased deposition and corrosion, flow-accelerated corrosion	Design (Sec. 7.11.2) Comm (Sec. 10.5; 10.8)

Table 2-1
Master List of Actions/Topics and Relevant Text Sections (continued)

General Subject	Specific Topic/Action	Rationale	To Avoid These Damage Mechanisms	Life Phase/ (Report Section)
XII. Instrumentation and Controls (cont.)	Design and install the required cycle chemistry instrumentation system based on the need to monitor key parameters. (Actions 8.2 and 9.7)	Will aid in the optimization of feedwater and HRSG treatments; minimize corrodant ingress and concentration, and reduce corrosion product generation and transport.	All waterside (internal) corrosion mechanisms.	Design (Sec. 8.2) Fab/Cons (Sec. 9.7)
	Automate startup and shutdown procedures and limit steam temperature ramp rates to the more restrictive of the HRSG or ST; confirm during commissioning (Actions 8.4a; 10.5; 10.8a; 10.8b).	Fatigue damage rates in HRSG components are strongly influenced by step changes and ramp rates. Appropriate controls can help perform reliable, quick startups and shutdowns without excessive damage to critical parts of the HRSG.	Creep fatigue, thermal fatigue, possible corrosion fatigue.	Design (Sec. 8.4) Comm (Sec. 10.5; 10.8)
	Provide HP and HRH bypass valves and ST HP and IP inlet control valves with demand HP saturation temperature characteristic with ramp rates acceptable to the HP steam drum. (Action 8.4b)	"	"	Design (Sec. 8.4)
	Automate the sequenced opening and closing of HP superheater and reheater drains, pipe drains, vents, etc. during coordinated startups; confirm during commissioning (Actions 8.4c; 10.2a; 10.5).	"	"	Design (Sec. 8.4) Comm (Sec. 10.2; Sec. 10.5)
	Automate the cooling of HP superheaters during normal shutdowns; confirm during commissioning (Actions 8.4d; 10.2a; 10.5)	"	"	Design (Sec. 8.4) Comm (Sec. 10.2; 10.5)

Key Failure Avoidance Actions

Table 2-1
Master List of Actions/Topics and Relevant Text Sections (continued)

General Subject	Specific Topic/Action	Rationale	To Avoid These Damage Mechanisms	Life Phase/ (Report Section)
XII. Instrumentation and Controls (cont.)	Consider the addition of replaceable temperature measuring probes for the HP drum and superheater outlet header to permit increased ramp rates. (Action 8.4e)	"	"	Design (Sec. 8.4)
	Install needed temporary thermocouples and instrumentation where needed during the commissioning process. (Action 10.2d; 10.8a; 10.8b)	To allow confirmation of the level of transient thermal stresses.	Primarily thermal fatigue and creep fatigue.	Comm (Sec. 10.2 ; 10.8)
XIII. Supports	Arrange panel support within modules to minimize thermally induced stresses in individual tube rows; confirm during commissioning (Actions 7.17a; 10.3b)	Minimizes the stresses developed in tubes when expanded from cold to hot operating conditions.	Creep fatigue, thermal fatigue, or corrosion fatigue	Design (Sec. 7.17) Comm (Sec. 10.3)
	For cycling HRSGs, use flexible supports for top-supported panel arrangements that develop differential expansion forces between tube rows. (Action 7.17b)	"	"	Design (Sec. 7.17)
XIV. Noise/ Vibration	Design all parts of plant to minimize vibrations, particularly HRSG walls and external pipelines. (Action 7.18)	Minimize fatigue damage and reduce noise levels.	Flow-induced vibration fatigue.	Design (Sec. 7.18)
XV. Transport and Storage	Establish and execute appropriate procedures to ensure adequate protection of HRSG components during transportation to the site and storage at the site during construction. (Action 9.2)	Prevent accumulation of contaminants in the cycle; prevent corrosion of pressure part surfaces; prevent accumulation of debris in pressure parts.	Corrosion processes; deposition, short term overheating from blockages.	Fab/Cons (Sec. 9.2)

3

DAMAGE AVOIDANCE BY MECHANISM

3.1 Overview and Use of this Chapter

The purpose of this chapter is to present specific damage avoidance actions for each of the possible failure or damage mechanisms. The material is adapted from the more detailed discussion of HRSG tube failure mechanisms contained in the *Heat Recovery Steam Generator Tube Failure Manual* [3-1] and from the relevant actions presented in Chapters 4-10.

The following mechanisms are covered:

Mechanism	Table Number
Corrosion Fatigue	3-1
Thermal Fatigue	3-2
Creep Fatigue	3-3
Flow-Induced Vibration Fatigue	3-4
Waterside and Steamside Oxide Growth and Deposits	3-5
Flow-Accelerated Corrosion	3-6
Acid Phosphate Corrosion	3-7
Caustic Gouging	3-8
Hydrogen Damage	3-9
Pitting	3-10
Gas-Side Corrosion	3-11
Acid Dewpoint Corrosion	3-12
Stress Corrosion Cracking	3-13
Short Term Overheating	3-14
Longterm Overheating	3-15
Thermal Quenching-Induced Fracture	3-16

Each table has four columns. The first indicates the appropriate life cycle stage – owner specification, design, fabrication/erection, commissioning, operations and maintenance. The second column provides the indicated action. A section or chapter number is provided to direct the reader to additional information in this report, where available, for each action. These references are generally to significant discussions of the topic. For those actions without specific references, there may still be material available in the report, see the index by subject in Chapter 2 for another approach to finding the required material.

The third column is titled “Objective”. This is why the action has been suggested. The final column is “Root Cause”. This final column is quite important, since the remedy for avoidance of any damage mechanism is inexorably tied to an underlying root cause. Most mechanisms have more than one potential or contributory root cause. The purpose of this column is to emphasize that the actions (second column) are tied directly to a particular underlying cause.

3.2 References

[3-1]. Dooley, R.B., K.J. Shields, S.R. Paterson, T.A. Kuntz, W.P. McNaughton, and M. Pearson, *Heat Recovery Steam Generator Tube Failure Manual*, 1004503, EPRI, Palo Alto, CA., 2002.

[3-2]. Dooley, R.B., A. Aschoff, M. Ball, A. Bursik, F. Pocock, and K.J. Shields, *Interim Cycle Chemistry Guidelines for Combined Cycle HRSGs*, TR-110051, EPRI, Palo Alto, CA., November 1998. [Note this reference is in Tables, not in preceding text].

Table 3-1
Overview of Actions to Avoid Corrosion Fatigue

Mechanism: Corrosion Fatigue

Brief Description of Mechanism: ID-initiated cracking that is a synergistic combination of cyclic loading and contact with corrosive liquid.

General Approaches to Avoidance: Reduce stresses/strains, reduce environmental contributors

Unit Life Cycle Stage	Actions (Report Sections for Detailed Information)	Objective	Relevant Root Cause
Owner Specification	- Require that the designer work together with the owner and gas/steam turbine vendors to define the characteristics of the “design basis operating transients”. (Sec. 4.2, 4.3) - Require dynamic simulations and design life calculations (using TRD 301 Annex 1 or equivalent approaches which include an evaluation of the potential for cracking of the waterside oxides) of all normal transients and anticipated trips. (Sec. 4.2, 4.3 and Chap. 7) - Require instrumentation & controls to monitor & control cycle chemistry during startups and shutdowns. (Sec. 8.2, 9.7) - Require cycle chemistry that meets the EPRI HRSG Cycle Chemistry Guidelines [3-2], including during startups. (Chapter 5) - Require that the HRSG has the proper hardware and procedures to meet the EPRI short and longterm layup guidelines [3-2]. (Sec. 4.3, 5.10, 10.6)	- Define the unit life mission and cycling characteristics. - Design that is flexible and has design details with low stress concentration factors. - Have a continuous monitoring/control system that can ensure that corrosive water is prevented during transient and steady state operation - To minimize frequency of poor chemistry operation. - Have the means and methods to prevent out-of-service pitting corrosion, which can act as initiating sites for corrosion fatigue.	- Excessive stresses/strains. - Excessive stresses/strains. - Poor water chemistry. - Poor water chemistry. - Improper shutdown and/or layup.

Table 3-1
Overview of Actions to Avoid Corrosion Fatigue (continued)

Unit Life Cycle Stage	Actions (Report Sections for Detailed Information)	Objective	Relevant Root Cause
Design	• Use detailed dynamic simulation, stress/strain analysis models to verify that the strain ranges meet the strain limits for water-touched components in TRD 301, Annex 1, or equivalent, for all design basis operating scenarios/cases. (Sec. 4.2, 4.3, Chap. 7) • Include adequately sized and properly located drains and associated valving. (Sec. 7.7) • Include equipment, monitors, and adequately programmed controls, to meet the EPRI cycle chemistry guidelines. (Sec. 8.2, 9.7) • Include equipment for nitrogen cap, thorough draining, or continuous circulation of treated water. • Prepare written documentation of logic used in the on-line cycle chemistry control systems, including PLCs. • Prepare written operating and short and longterm layup procedures. (Sec. 4.3, 5.10)	• Ensure that the peak cyclic strains are low enough to prevent cracking of the waterside oxide scale. • To minimize condensate formation during shutdown and subsequent forward flow during startups. • To minimize the frequency of corrosive water, than can chemically disrupt the waterside oxide. • Same as above. • Same as above. • Same as above.	• Excessive stresses/strains. • Improper shutdown and/or layup. • Poor water chemistry. • Improper shutdown and/or layup. • Poor water chemistry. • Improper shutdown and/or layup.
Fabrication/Erection	• Ensure that any field modifications are reviewed by the Engineer for conformance with TRD301, Annex 1, or equivalent. • Ensure that the weld quality (especially with regard to excess weld root reinforcement, incomplete penetration, or incomplete fusion) is within the design requirements. (Sec. 7.16) • Ensure that hydrotest water is properly treated and is fully drained immediately following testing. (Sec. 10.6) • Perform adequate chemical cleaning and passivation treatments. (Sec. 5.10; 9.5)	• Don't allow as-built configuration to have less flexibility or higher peak cyclic stress range than the design. • Don't allow the introduction of crevices or root profiles that will create corrosion cells or stress concentrators. • Don't allow conditions that will lead to pre-service corrosion. • Ensure that all potential corrosion cells, such as from mill scale or debris are eliminated and the water-touched surfaces of the tubing enters service with an intact protective waterside oxide scale.	• Excessive stresses/strains. • Excessive stresses/strains; poor water chemistry. • Similar to improper shutdown and/or layup. • Breakdown of protective oxide scale.

Table 3-1
Overview of Actions to Avoid Corrosion Fatigue (continued)

Unit Life Cycle Stage	Actions (Report Sections for Detailed Information)	Objective	Relevant Root Cause
Commissioning	• Verify that the design flexibility and peak strain range values have been achieved by measuring temperatures, strains and/or displacements of key components and hot spot stress locations during every design basis operating transient test. (Sec. 10.2, 10.3) • Verify evaporator chemistries are optimized and that pH transients do not occur during shutdowns and startups. (Sec. 10.6)	• Ensure that peak cyclic strains are within an acceptable range. • To minimize the frequency of poor chemistry operation	• Excessive stresses/strains. • Non-optimum evaporator / economizer chemistry.
Operations	• Follow optimized cycle chemistry and confirm against EPRI's Cycle Chemistry Guidelines [3-2]. • Ensure that the operation during stops and starts is no more severe than the design basis operating transients. • Monitor and maintain drum level control to minimize mechanical carryover into the steam-touched tubing. • Follow the specified shutdown and layup procedures.	• To minimize the frequency of low pH, high dissolved oxygen conditions, especially during startups. • Don't introduce high strain ranges during unit transients. • To minimize the possibility of deposits in the steam-touched tubing that may acidify if moisture is ever present. • Have the means and methods to prevent out-of-service pitting corrosion.	• Non-optimum chemistry • Excessive stresses/strains. • Breakdown of protective oxide scale. • Improper shutdown and/or layup.
Maintenance	• Periodically inspect the header/tubing attachments, header/drum internals and selected tube internal surfaces to ensure that: (i) tube deformation or temporary field repairs/modifications are not leading to a loss of flexibility or condensate/water draining capability, (ii) steam separators are intact and minimizing mechanical carryover, (iii) slip-type connections are not locking up, (iv) there is no evidence of mechanical disruption of the waterside oxide scale, (v) there is no standing water or condensate in the tubing during outages, (vi) there is no deposition/ pitting/ oriented pitting/ cracking on the inside diameter surfaces of the tubing, (vii) maintenance debris is not introduced into the pressure parts.	• Ensure that the flexibility, water/Steamside scale, and drum steam separation internals do not degrade. • Ensure that corrosive water/condensate and corrosion initiating conditions such as deposit buildup or maintenance debris are not present.	• Excessive stresses/strains; poor water and steam chemistry.

Damage Avoidance by Mechanism

Table 3-2
Overview of Actions to Avoid Thermal Fatigue

Mechanism: Thermal Fatigue

Brief Description of Mechanism: OD-initiated cyclic damage caused by thermal expansion/contraction-induced strains

General Approaches to Avoidance: Reduction of restraint stresses; improved operating procedures; reduced cyclic stresses.

Unit Life Cycle Stage	Actions	Objective	Relevant Root Cause
Owner Specification	- The designer and owner should work together along with gas/steam turbine vendors to define the characteristics of the “design basis operating transients”. (Sec. 4.2, 4.3) - Specify that the design must conform to BS5000, Annex C, or equivalent for all design basis operating transients. (Sec. 4.2, 4.3, Chap. 7) - Include analysis of expected life for chosen material and design details. (Chap. 4, 7)	- Define the unit life mission and cycling characteristics, and obtain a design that is flexible and has design details with low stress concentration factors. - To obtain a proper analysis of thermal transients and expected lifetime. - To obtain a design that has the optimal materials, wall thicknesses, and geometry transitions.	- Excessive restraint and thermal stresses; influence of unit operation. - Excessive thermal stresses; operation. - Excessive restraint stresses.
Design	- Perform design calculations that demonstrate conformance to BS5500, Annex C, or equivalent. (Chap. 4, 7) - Prepare cyclic life expenditure curves for all thick section pressure parts (i.e., tube to header connections, header boreholes). (Chap. 7, particularly Sec. 7.4) - Include the cyclic life expenditure curves in the operator’s manual along with startup and shutdown requirements. (Sec. 4.3) - Ensure that proper drains, vents, sparging systems, startup feedwater preheating capability, etc., have been included in design, and that operating procedures provide adequate coverage for these components. (Sec. 7.7, 7.11)	- Design that is flexible and has construction details with low stress concentration factors. - Estimate the allowable combinations of temperature change and rate of temperature change and relate this back to measurable/ controllable operating parameters. - Establish appropriate operating procedures, particularly for transients. - Minimize the potential for excessive thermal transients resulting from introduction of hot fluid into cold pressure parts or cold fluids into hot pressure parts or imbalanced fluid temperatures into banks of tubing.	- Excessive restraint stresses. - Influence of unit operation. - Influence of unit operation. - Excessive thermal stresses.

Table 3-2
Overview of Actions to Avoid Thermal Fatigue (continued)

Unit Life Cycle Stage	Actions	Objective	Relevant Root Cause
Design (con't)	• Include thermal shock measuring thermocouples in the low pressure economizer inlet and the high pressure superheater outlet headers.	• Include instrumentation that will allow the cyclic life expenditure of the low pressure economizer inlet header and high pressure superheater outlet header to be monitored.	• Excessive thermal stresses.
Fabrication/Erection	• Ensure the as-built configuration is within the design limits, especially with regard to attachments, and weld connections, and flexible supports such as pipe/header spring hangers.	• Ensure flexible/low stress concentration factor as-built configuration.	• Excessive restraint stresses.
Commissioning	• Monitor installed thermocouples on selected low pressure economizer and high pressure superheater inlet and outlet header stub tubes during all commissioning tests to ensure that the tube temperatures, the distribution of tube temperature, and the rates of change of temperatures are within the design limits. (Sec. 10.2, 10.3)	• To verify that the design/control/operating parameters will prevent excessive thermal transients.	• Excessive thermal stresses; influence of unit operation, particularly transients.
Operations	• Ensure that the operation is within the design limits or review the actual operation and determine the effect on the cyclic life.	• Balance the cyclic life goals with the dispatch goals.	• Influence of unit operation, particularly transients.
Maintenance	• Periodic inspection for evidence of thermal fatigue, particularly at tube-to-header connections and tube attachments.	• Detect damage as early as possible so that additional needed modifications can be made.	• All of the above.

Damage Avoidance by Mechanism

Table 3-3
Overview of Actions to Avoid Creep Fatigue

Mechanism: Creep Fatigue

Brief Description of Mechanism: OD-initiated synergistic damage occurring during cyclic loading in high temperature locations.

General Approaches to Avoidance: Reducing local temperatures, lower cyclic stresses; reduce local stress concentrations.

Unit Life Cycle Stage	Actions	Objective	Relevant Root Cause
Owner Specification	- The designer and owner should work together along with gas/steam turbine vendors to define the characteristics of the “design basis operating transients”. (Sec. 4.2, 4.3) - Specify that the design of all pressure parts operating within their creep temperature regime must conform to ASME Section III, Division 1, Subsection NH for all design basis operating transients, or equivalent. (Chap. 4, 7)	- Define the unit life mission and cycling characteristics, and obtain a design that is flexible and has design details with low stress concentration factors. - Design that has the optimal materials, wall thicknesses, and geometry transitions.	- Excessive temperatures, restraint stresses; effect of operation. - Same.
Design	- Perform design calculations that demonstrate conformance to ASME Section III, Division 1, Subsection NH, or equivalent. For alloys not considered in Subsection NH, collect material property information with enough coverage to duplicate the Subsection NH methods. (Chap. 4, 7) - Prepare cyclic life expenditure curves for all thick section pressure parts (i.e., tube to header connections, header boreholes). (Sec 7.4) - Include the cyclic life expenditure curves in the operator’s manual along with startup and shutdown requirements. (Sec. 4.3) - Ensure that proper drains, vents, etc. have been included in the design, and that designed operating procedures provide adequate coverage for these components. (Sec. 7.7, 7.11)	- Design that is flexible and has construction details with low stress concentration factors. - Estimate the allowable combinations of temperature change and rate of temperature change and relate this back to measurable/ controllable operating parameters. - Same - Minimize the potential for excessive thermal transients resulting from introduction of hot fluid into cold pressure parts or cold fluids into hot pressure parts or imbalanced fluid temperatures into banks of tubing..	- Excessive restraint stresses. - Influence of unit operations. - Influence of unit operations. - Excessive thermal stresses.

Table 3-3
Overview of Actions to Avoid Creep Fatigue (continued)

Unit Life Cycle Stage	Actions	Objective	Relevant Root Cause
Design (cont.)	• Include thermal shock measuring thermocouples into the low pressure economizer inlet and the high pressure superheater outlet headers. (Sec. 10.2) • Perform design calculations (include upset and unbalanced conditions) of the bulk steam temperature, and tube metal temperature as a function of gas touched length to ensure that there are sufficient creep life and oxidation resistance margins for the tube and header alloys selected. • Include adequate weld performance factors in the design, especially for weld connections made between alloys with more than a few percent difference in chromium content. (Sec. 9.4)	• Include instrumentation that will allow the cyclic life expenditure of the low pressure economizer inlet header and high pressure superheater outlet header to be monitored. • Ensure that there are sufficient design margins to prevent excessive oxidation or creep for the alloys and temperatures. • Ensure that there are sufficient design margins to prevent excessive stresses at welds.	• Excessive thermal stresses. • Excessive temperatures for material. • Excessive thermal stresses.
Fabrication/Erection	• Ensure the as-built configuration is within the design limits, especially with regard to attachments, and weld connections, and flexible supports such as pipe/header spring hangers. • Ensure that the welding procedure specifications and post weld heat treatments are adequate and are closely followed, especially for components with chromium contents above 2%. (Sec. 9.4)	• Ensure flexible/low stress concentration factor as-built configuration. • Avoid high residual stresses, undesirable microstructures, etc.	• Excessive restraint stresses. • Excessive thermal stresses.
Commissioning	• Monitor installed thermocouples on selected high pressure superheater inlet and outlet header stub tubes during all commissioning tests to ensure that the tube temperatures, the distribution of tube temperature, and the rates of change of temperatures are within the design limits. (Sec. 10.2, 10.3)	• To verify that the design/control/operating parameters will prevent excessive thermal transients.	• Excessive thermal stresses; excessive temperatures; influence of unit operation, particularly transients.
Operations	• Ensure that the operation is within the design limits or review the actual operation and determine the effect on the cyclic life.	• Balance the cyclic life goals with the dispatch goals.	• Influence of unit operation, particularly transients.

Damage Avoidance by Mechanism

Table 3-3
Overview of Actions to Avoid Creep Fatigue (continued)

Unit Life Cycle Stage	Actions	Objective	Relevant Root Cause
Maintenance	• Periodically examine the tube, header and piping supports, attachments, and slip connections to ensure that they are still functioning properly. • If unanticipated transients have occurred or other conditions suggest that thermal fatigue damage may have initiated, perform appropriate non-destructive examinations of suspect tube to header connections, header boreholes, and attachments.	• Don't allow corrosion, debris buildups, thermal deformation, etc. change the flexibility and thermal restraint of the pressure parts • Detect damage early so that life optimization corrective actions can produce a significant improvement and so through wall failures are prevented	• Excessive thermal stresses; stress concentrations. • Influence of unit operation, particularly transients.

Table 3-4
Overview of Actions to Avoid Flow-Induced Vibration

Mechanism: Flow-Induced Vibration Fatigue

Brief Description of Mechanism: Cyclic damage resulting from tube vibration.

General Approaches to Avoidance: Tuning and damping of affected structure; modifying gas velocities.

Unit Life Cycle Stage	Actions	Objective	Relevant Root Cause
Owner Specification	Require that the gas velocity, natural frequency, vortex shedding frequency, and damping coefficient for all sections/bundles of tubing be determined and adjusted to prevent flow-induced vibration under all design basis operating cases. (Sec. 7.18)	Ensure that the vortex shedding frequency is not near the fundamental natural frequency of the tubing.	Combination of gas velocity and tube characteristics.
Design	- Perform design checks for flow-induced vibration. (Sec. 7.18) - Use damping fixtures such as staking that will ensure that flow-induced vibration will not occur.	- To avoid a critical confluence of gas velocity, tube dimensions, support spacing, and damping. - To optimize use of damping as a mitigation choice.	- Same as above. - Same as above.
Fabrication/Erection	Ensure that the as-built configuration is within the specified design limits, especially with regard to the tubing/fin configurations and vibration damping fixtures.	To avoid a critical confluence of gas velocity, tube dimensions, support spacing, and damping.	Same as above.
Commissioning	If evidence of flow-induced vibration (unusual noise or vibration, or visual evidence of high frequency/low displacement motion/rubbing between tubes and vibration dampers/tube supports) is present, perform measurements of the natural frequency and tubing displacements/strain. (Sec. 7.18)	To detect and fix the problem before crack initiation occurs.	Same as above.
Operations	- Operate within the design basis gas flow conditions. - If vibration is felt/heard/seen then either return the unit back to its design basis flow conditions or remove the HRSG from service and perform an examination of the tubing and vibration damping fixtures.	- To ensure that off-design gas velocities do not occur. - To ensure that the extent of time that vibration occurs is minimized (i.e., to prevent crack initiation).	- Gas velocities at critical values. - Combination of gas velocity and tube characteristics.

Table 3-4
Overview of Actions to Avoid Flow-Induced Vibration (continued)

Unit Life Cycle Stage	Actions	Objective	Relevant Root Cause
Maintenance	- Periodically examine and maintain the tube supports and vibration damping fixtures. - If flow-induced vibration has occurred, perform wet fluorescent magnetic particle examination of the selected tube to header connections and other design details, such as tube supports, where high vibration-induced cyclic strains may occur.	- Make sure that the damping characteristics of the tube bundles do not change over time due to a change of slip/friction between the tubing and supports/damping fixtures resulting from wear, corrosion, or debris buildup. - To ensure that any damage that does occur is detected prior to becoming widespread and before throughwall failures occur.	- Tube vibration characteristics. - Combination of gas velocity and tube characteristics.

Table 3-5
Overview of Actions to Avoid Excessive Internal Deposits

Mechanism: Excessive Internal Deposits

Brief Description of Mechanism: Progressive deposits of water/steam impurities or oxide scale buildup, which can contribute to a variety of damage mechanisms.

General Approaches to Avoidance: Avoid water/steam contamination, optimize cycle chemistry, optimize layup and shutdown procedures, avoid elevated temperature operation, minimize sources of flow disruption.

Unit Life Cycle Stage	Actions	Objective	Relevant Root Cause
Owner Specification	Specify appropriate hardware to achieve cycle chemistry targets. Ensure EPRI HRSG Cycle Chemistry Guidelines [3-2] are included in specification. (Sec. 8.2, 9.7)	To control the contamination of the water and steam throughout the cycle and thus minimize potential for deposition.	Deficiencies in cycle chemistry.
Design	- Optimize entire cycle chemistry effort - choice of feedwater and HRSG treatments, control during operation, layup, and shutdown, appropriate monitor systems, choice of appropriate ancillary hardware (condensate polishers, makeup water treatment, deaeration, etc.) (Chap. 5) - Establish proper attemperation practices. (Sec. 7.9)	- To control the contamination of the water and steam throughout the cycle and thus minimize potential for deposition. - To avoid locally high temperature regimes.	- Deficiencies in cycle chemistry. - Elevated metal temperatures.
Fabrication/Erection	- Minimize construction methods that can cause flow disruptions. - Pre-operational cleaning to remove deposits. (Sec. 9.5)	- To minimize flow disruption. - Prevent deposits.	- Flow disruption. - Existing deposits.
Commissioning	- Monitor feedwater and evaporator chemistries, particularly for feedwater corrosion products, during operation and transients. (Sec. 10.6) - Evaluate whether combustion gas flow irregularities (such as laning) are resulting in locally high temperatures. (Sec. 10.7)	- Minimize transport to the evaporator, which will minimize deposits. - To avoid locally high tube temperatures.	- Precursor to underdeposit corrosion mechanisms. - Elevated metal temperatures.
Operations	- Use optimized cycle chemistry. - Avoid elevated tube metal temperatures. - Avoid contamination of steam.	- Prevent contamination. - To avoid locally high temperature regimes that can promote deposition/scale formation. - Prevent contamination and deposition.	- Contamination. - High metal temperatures. - Contamination.

Damage Avoidance by Mechanism

Table 3-5
Overview of Actions to Avoid Excessive Internal Deposits (continued)

Unit Life Cycle Stage	Actions	Objective	Relevant Root Cause
Maintenance	• Periodic inspection (fiber optics, etc.) and tube sampling for evidence of significant deposition, fouling, or corrosion. • Periodic use of proper chemical cleaning to remove deposit buildup.	• Identify locations of deposits. • Remove deposits.	• Accumulating deposits. • Accumulating deposits.

Table 3-6
Overview of Actions to Avoid Flow-Accelerated Corrosion

Mechanism: Flow-Accelerated Corrosion

Brief Description of Mechanism: Dissolution of protective internal oxide with subsequent corrosion of tube material and loss of wall thickness.

General Approaches to Avoidance: Primarily proper choice and control of feedwater and HRSG evaporator water treatments; some materials solutions for intractable cases.

Unit Life Cycle Stage	Actions	Objective	Relevant Root Cause
Owner Specification	Require FAC analysis as part of the design package. Ensure EPRI HRSG Cycle Chemistry Guidelines [3-2] are included in specification. (Chap. 5)	Require a clear understanding of potentially susceptible locations.	Water chemistry (reducing conditions), hydrodynamics; susceptible material; temperature.
Design	- Design cycle chemistry program to avoid reducing conditions, including eliminating reducing agent and designing for an oxidizing environment for all-ferrous systems, to prevent single phase FAC. For possible two phase FAC, design for possible injection of phosphate or caustic into evaporator drums. (Chap. 5) - Identify high velocity locations and determine whether the tube material needs to include a resistant (chromium containing) alloy, in addition to cycle chemistry actions.	- Prevent localized dissolution of protective oxide and initiation of the corrosion process. - Clearly understand potentially susceptible locations and design-in protection via velocity reduction or material choice, if chemistry options will not be sufficient.	- Water chemistry (reducing conditions). - Hydrodynamics; susceptible material; temperature.
Fabrication/ Erection	- Install appropriate cycle chemistry monitoring systems. (Sec. 8.2, 9.7) - Ensure that resistant material is applied in correct (high velocity and turbulence) locations.	- Preparation for measuring key cycle chemistry parameters. - Minimize susceptibility of target locations.	- Water chemistry (reducing conditions). - Susceptible material in susceptible location.
Commissioning	Measure key cycle chemistry parameters (iron, oxygen, cation conductivity, and oxidizing-reducing potential). (Sec. 10.6)	To ensure the appropriate environment is in place to prevent the occurrence of FAC.	Water chemistry.
Operations	Continuing evaluation of key cycle chemistry parameters as in "Commissioning" above.	To ensure the appropriate environment is in place to prevent the occurrence of FAC.	Water chemistry.
Maintenance	Periodic inspection (ultrasonic wall thickness testing, internal fiber optics) at susceptible locations.	To ensure that wall thinning due to FAC is not occurring.	Susceptible material in susceptible location.

Damage Avoidance by Mechanism

Table 3-7
Overview of Actions to Avoid Acid Phosphate Corrosion

Mechanism: Acid Phosphate Corrosion

Brief Description of Mechanism: Combination of internal deposits plus a concentration of phosphate salts leads to underdeposit corrosion and eventual tube failure.

General Approaches to Avoidance: Minimize feedwater corrosion products to limit deposit formation; appropriate cycle chemistry controls to minimize phosphate concentrations; avoidance of locally high temperatures.

Unit Life Cycle Stage	Actions	Objective	Relevant Root Cause
Owner Specification	Specify that only tri-sodium phosphate will be used and allow for injection into evaporator drums [3-2].	To ensure that acid phosphates will not be used.	Incorrect phosphate treatment.
Design	Optimize entire cycle chemistry effort – choice of feedwater and HRSG treatments for each pressure circuit, control during operation, layup, and shutdown, use of appropriate monitoring systems, choice of appropriate ancillary hardware (condensate polishers, makeup water treatment, deaeration, etc.) (Chap. 5)	To optimize the cycle chemistry throughout the cycle and thus minimize the potential for deposition and concentration of acidic phosphates.	Improper phosphate treatments and additions and deposit concentrations sites for acid phosphate corrosion.
Fabrication/ Erection	Avoid use of weld details that could cause flow disruption, such as internally protruding weld beads, etc.	To prevent deposition from initiating.	Flow disruption & formation of deposits.
Commissioning	- Establish optimum chemistry, controls, monitoring instrumentation, procedures, and action levels in a program to minimize contaminant levels, corrosion product formation and transport and the formation of deposits. (Sec. 10.6) - Establish optimum shutdown and layup procedures. (Sec. 10.6) - Measure carryover rates for each drum (in multi-pressure HRSG units). Monitor feedwater and evaporator contaminant levels to verify compliance with specifications and suitability of chemical treatment and operating practices. (Sec. 10.6) - Eliminate areas of localized overheating caused by firing auxiliary fuels and firing equipment (duct burners). (Sec. 10.7)	- To develop optimum phosphate treatment for each evaporator. - To minimize corrosion and subsequent transport of contaminant on startup; prevent formation of deposits on startup. - To control impurity level and establish evaporator control curves. - To prevent formation of local hot spots that can lead to excessive rates of deposits.	- Incorrect phosphate treatment. - Excessive deposits. - Concentration of impurities. - Accelerated deposit formation.

Table 3-7
Overview of Actions to Avoid Acid Phosphate Corrosion (continued)

Unit Life Cycle Stage	Actions	Objective	Relevant Root Cause
Operations	• Monitor impurity levels through appropriate instrumentation. • Use chemistry control logs to detect whether there is an ongoing problem with phosphate hideout. Monitoring parameters to review include pH, phosphate level and specific conductivity as a function of load. • Don't use mono-sodium phosphate or an excess of bi-sodium phosphate as a control technique. • Be aware that changes in fuel firing that create higher heat transfer rates may initiate deposition in previously clean HRSG tubes. • Revise operating procedures to minimize metal temperature excursions above design values.	• To control the level of impurities in the HRSG water and steam. • Minimize potential for excessive levels of phosphate. • Minimize potential for concentration of acidic phosphates within deposits. • To prevent formation of local hot spots that can lead to excessive rates of deposits. • To prevent formation of local hot spots that can lead to excessive rates of deposits.	• Excessive deposits and concentration of impurities. • Improper phosphate treatments and additions. • Improper phosphate treatments and additions. • Accelerated deposit formation. • Accelerated deposit formation.
Maintenance	• Perform periodic inspection (fiber optics, etc.) and/or selective evaporator tube sampling from suspect regions to measure deposition. • Establish chemical cleaning procedures to be used when deposits exceed established levels and perform chemical cleaning at appropriate intervals. • Perform gas side maintenance to avoid improper heat distribution or circulation.	• Early detection of a developing problem. • Removal of deposits before the underdeposit corrosion process can begin removing tube materials. • To prevent formation of local hot spots that can lead to excessive rates of deposits.	• All root causes. • Control deposits. • Prevent deposit formation.

Damage Avoidance by Mechanism

Table 3-8
Overview of Actions to Avoid Caustic Gouging

Mechanism: Caustic Gouging

Brief Description of Mechanism: Combination of internal deposits plus a concentration of caustic to high pH levels leads to underdeposit corrosion and eventual tube failure.

General Approaches to Avoidance: Minimize feedwater corrosion products to limit deposit formation; appropriate cycle chemistry controls to minimize caustic levels; avoidance of locally high temperatures.

Unit Life Cycle Stage	Actions	Objective	Relevant Root Cause
Owner Specification	Design facilities for the injection of NaOH. Ensure EPRI HRSG Cycle Chemistry Guidelines [3-2] are included in specification. (Chap. 5)	To ensure NaOH in HP evaporators is less than 2 ppm.	Concentration of NaOH within deposits.
Design	- Optimize entire cycle chemistry effort – choice of feedwater and HRSG treatments, control during operation, layup, and shutdown, use of appropriate monitoring systems, choice of appropriate ancillary hardware (condensate polishers, makeup water treatment, deaeration, etc.). (Chap. 5) - Develop optimum HRSG treatment for each pressure circuit. (Sec. 5.6, 5.7, 5.8)	- To optimize the cycle chemistry throughout the cycle and thus minimize the potential for deposition and concentration of NaOH. - To minimize caustic levels in evaporator circuits where NaOH is used.	- Deposit concentration sites for caustic gouging. - Excessive caustic concentration.
Fabrication/Erection	Avoid use of weld details that could cause flow disruption, such as internally protruding weld beads, etc.	To prevent deposition from initiating.	Flow disruption & formation of deposits.
Commissioning	- Establish optimum chemistry, controls, monitoring instrumentation, procedures, and action levels to minimize contaminant levels and the formation of deposits. (Sec. 10.6) - Establish optimum shutdown and layup procedures. (Sec. 10.6) - Measure carryover rates for each drum (in multi-pressure HRSG units). Monitor feedwater and evaporator contaminant levels to verify compliance with specifications and suitability of chemical treatment and operating practices. (Sec. 10.6) - Eliminate areas of localized overheating caused by firing auxiliary fuels and firing equipment. (Sec. 10.7)	- To develop optimum caustic treatment for each evaporator. - To minimize corrosion and subsequent transport of contaminant on startup; prevent deposits on startup. - To control impurity level and establish control curves. - To prevent formation of local hot spots that can lead to excessive rates of deposits.	- Incorrect caustic treatment. - Excessive deposits. - Concentration of impurities. - Accelerated deposit formation.

Table 3-8
Overview of Actions to Avoid Caustic Gouging (continued)

Unit Life Cycle Stage	Actions	Objective	Relevant Root Cause
Operations	• Monitor impurity levels through appropriate instrumentation. • Use chemistry control logs, on-line cycle chemistry records or instrumentation alarms to detect whether there is an ongoing problem with: - elevated caustic for units on caustic treatment - excessive caustic addition to AVT during startup and to overcome contamination - excessive caustic use as a control chemical for units on phosphate treatment. - ingress of caustic from regeneration of ion exchange resin for condensate polishers or makeup water. - Monitoring parameters to review include sodium hydroxide. • Be aware that changes in fuel firing that create higher heat transfer rates may initiate deposition in previously clean HRSG tubes. • Revise operating procedures to minimize metal temperature excursions above design values.	• To control the level of impurities in the HRSG water and steam. • To minimize caustic levels to less than 2 ppm. • To prevent formation of local hot spots that can lead to excessive rates of deposits. • To prevent formation of local hot spots that can lead to excessive rates of deposits.	• Excessive deposits and concentration of impurities. • Excessive caustic concentration. • Accelerated deposit formation. • Accelerated deposit formation.
Maintenance	• Perform periodic inspection (fiber optics, etc.) and/or selective evaporator tube sampling from suspect regions to measure deposition. • Establish chemical cleaning procedures to be used when deposits exceed established levels and perform chemical cleaning at appropriate intervals. • Perform gas side maintenance to avoid improper heat distribution or circulation.	• Early detection of a developing problem. • Removal of deposits before the underdeposit corrosion process can begin removing tube materials. • To prevent formation of local hot spots that can lead to excessive rates of deposits.	• All root causes. • Control deposits. • Prevent deposit formation.

Damage Avoidance by Mechanism

Table 3-9
Overview of Actions to Avoid Hydrogen Damage

Mechanism: Hydrogen Damage

Brief Description of Mechanism: Combination of internal deposits plus either contaminant ingress and/or a low pH acidic concentration leads to underdeposit corrosion and eventual tube failure.

General Approaches to Avoidance: Minimize feedwater corrosion products to limit deposit formation; appropriate cycle chemistry controls to minimize low pH excursions; avoidance of locally high temperatures.

Unit Life Cycle Stage	Actions	Objective	Relevant Root Cause
Owner Specification	- Specify a condensate polisher to help maintain appropriate levels of impurities, aid in mitigating condenser leakage, improving startup time, reducing blowdown, and reducing the need for chemical cleaning. (Sec. 5.5) - Specify a leak-tight, titanium-tubed condenser. (Sec. 5.5)	- To control the level of impurities in the HRSG water and steam. - Same as above	- Formation of excessive deposits, contaminant inleakage. - Same as above
Design	- Optimize entire cycle chemistry effort – choice of feedwater and HRSG treatments, control during operation, layup, and shutdown, use of appropriate monitoring systems, choice of appropriate ancillary hardware (condensate polishers, makeup water treatment, deaeration, etc.) (Chap. 5) - Develop optimum HRSG treatment for each pressure circuit. (Sec. 5.6, 5.7, 5.8)	- To control the contamination of the IP or HP evaporator water and minimize the potential for deposition. - To minimize the potential for contaminant levels above evaporator control curves or low pH excursions.	- Deposit concentration sites and/or contaminant ingress. - Deposits and acid contamination.
Fabrication/Erection	Avoid use of weld details that could cause flow disruption such as backing bars, internally protruding weld beads, etc.	To prevent deposition from initiating.	Flow disruption & formation of deposits.
Commissioning	- Establish optimum chemistry, controls, monitoring instrumentation, procedures, and action levels in a program to minimize contaminant levels and the formation of deposits. (Sec. 10.6) - Establish optimum shutdown and layup procedures. (Sec. 10.6)	- To develop optimum treatment and control the level of impurities in the HRSG IP and HP evaporators. - To minimize corrosion and subsequent transport of contaminant on startup; prevent subsequent formation of waterside and steamside deposits on startup.	- Excessive deposits and contamination. - Excessive deposits.

Table 3-9
Overview of Actions to Avoid Hydrogen Damage (continued)

Unit Life Cycle Stage	Actions	Objective	Relevant Root Cause
Commissioning (cont.)	• Measure carryover rates for each drum (in multi-pressure HRSG units). Monitor feedwater and evaporator contaminant levels to verify compliance with specifications and suitability of chemical treatment and operating practices. (Sec. 10.6) • Eliminate areas of localized overheating caused by firing auxiliary fuels and firing equipment (duct burners). (Sec. 10.7)	• To control impurity level and establish control curves. • To prevent formation of local hot spots that can lead to excessive rates of deposits.	• Concentration of impurities. • Accelerated deposit formation.
Operations	• Monitor impurity levels through appropriate instrumentation. • Use chemistry control logs to detect potential for chlorides from condenser leaks or water treatment plant breakdown. Monitoring parameters to review include extent and depth of pH and cation conductivity. • Be aware that changes in fuel firing that create higher heat transfer rates may initiate deposition in previously clean HRSG tubes. • Revise operating procedures to minimize metal temperature excursions above design values.	• To control the level of impurities in the HRSG water and steam. • Early detection of incidents of low pH excursions or knowledge that contaminant levels (Cl, SO₄) are above the evaporator normal control curves. • To prevent formation of local hot spots that can lead to excessive rates of deposits. • To prevent formation of local hot spots that can lead to excessive rates of deposits.	• Excessive deposits and concentration of impurities. • Acid contamination. • Accelerated deposit formation. • Accelerated deposit formation.
Maintenance	• Perform periodic inspection (fiber optics, etc.) and/or selective evaporator tube sampling from suspect regions to measure deposition. • Establish chemical cleaning procedures to be used when deposits exceed established levels and perform chemical cleaning at appropriate intervals. • Perform gas side maintenance to avoid improper heat distribution or circulation.	• Early detection of a developing problem. • Removal of deposits before the underdeposit corrosion process can begin removing tube materials. • To prevent formation of local hot spots that can lead to excessive rates of deposits.	• All root causes. • Control deposits. • Prevent deposit formation.

Damage Avoidance by Mechanism

Table 3-10
Overview of Actions to Avoid Pitting

Mechanism: Pitting

Brief Description of Mechanism: Localized dissolution of metal (corrosion) distinguished by high aspect ratio (depth to area ratio) of damage.

General Approaches to Avoidance: Avoiding stagnant, oxygenated water conditions both pre-service as well as during shutdown/layup, use of proper chemical cleaning techniques, avoiding deposition of sodium sulfate and subsequent formation of acidic solution. Most important is to provide shutdown protection.

Unit Life Cycle Stage	Actions	Objective	Relevant Root Cause
Owner Specification	Require consideration of pitting as part of the design package. Ensure EPRI HRSG Cycle Chemistry Guidelines [3-2] are included in specification. Ensure shutdown protection is defined in specification. (Chap. 5)	Require a clear understanding of conditions, which can lead to pitting.	Oxygen pitting, chemical cleaning pitting, sodium sulfate pitting
Design	- Develop proper shutdown and layup procedures. Ensure equipment to provide shutdown protection is provided in the design. (Sec. 4.3, 5.10, 10.6) - Develop proper chemical cleaning procedures. (Sec. 4.6, 5.10, 9.5)	- To avoid the formation of stagnant, oxygenated water with no protective environment (such as nitrogen blanket). - To avoid chemical cleaning errors (use of inappropriate cleaning agent, excessively strong acid, excessively long cleaning times, too high a temperature, failure to neutralize, drain and rinse after cleaning, breakdown of inhibitors).	- Oxygen pitting from improper shutdown. - Improper chemical cleaning process.
Fabrication/ Erection	Protect tubes against corrosion during transport, storage, erection and after hydrotesting of completed tube assemblies. (Sec. 9.2)	To avoid the formation of stagnant, oxygenated water on the tube surface.	Oxygen pitting.
Commissioning	- Measure key cycle chemistry parameters (oxygen, cation conductivity, and sodium). Test installed shutdown protection. (Sec. 10.6) - Confirm that condensate polisher and other chemistry control devices are not allowing slippage of sodium sulfate. (Sec. 10.6)	- To confirm shutdown procedures, and to evaluate whether sodium carryover is occurring. - To avoid carryover of sodium sulfate.	- Oxygen pitting, sodium sulfate pitting. - Sodium sulfate pitting.

Table 3-10
Overview of Actions to Avoid Pitting (continued)

Unit Life Cycle Stage	Actions	Objective	Relevant Root Cause
Operations	• Continuing evaluation of key cycle chemistry parameters. • Use appropriate shutdown and layup procedures (nitrogen blanketing, draining, drying, etc.).	• To detect excessive oxygen or sodium levels. • To avoid formation of stagnant, oxygen-saturated water.	• Oxygen pitting, sodium sulfate pitting. • Oxygen pitting from improper shutdown.
Maintenance	• Periodic tube sampling or fiber optic surveys. • Ensure proper performance of periodic chemical cleaning operations.	• To detect damage initiation. • To prevent pitting from chemical cleaning.	• All root causes. • Improper chemical cleaning process.

Damage Avoidance by Mechanism

Table 3-11
Overview of Actions to Avoid Gas-Side Corrosion

Mechanism: Gas-Side Corrosion

Brief Description of Mechanism: Generalized or localized external corrosion, typically by chlorides or sulfur compounds.

General Approaches to Avoidance: Minimize source of corrodent; upgrade to more resistance material.

Unit Life Cycle Stage	Actions	Objective	Relevant Root Cause
Owner Specification	Require consideration of gas-side corrosion as part of the design package. (Sec. 6.2)	Require a clear understanding of conditions which can lead to gas-side corrosion.	Introduction of corrosive species.
Design	- Specify thicker tube if corrosion anticipated (such as for units designed to dual fire with oil). (Sec. 6.2) - Consider upgrading material to more resistant grade if significant sulfur bearing oil co-firing is anticipated. (Sec. 6.2)	- Improved corrosion allowance. - To avoid excessive corrosion rates.	- All root causes. - Supplemental or co-firing with sulfur containing fuel.
Fabrication/ Erection	None		
Commissioning	Evaluate whether ammonia slip is occurring when an SCR is installed.	To anticipate the formation of ammonium sulfates.	Formation of ammonium sulfates.
Operations	- Lessen amount of oil firing. - Change oil fired to lower sulfur content. - Change SCR procedures to lessen ammonia slip - Decrease or eliminate the use of CO catalysts with the SCR. - Locate the CO catalyst downstream of the SCR.	- To decrease the formation of sulfates. - To decrease the formation of sulfates. - To decrease the formation of ammonium sulfates.	- Supplemental or co-firing with sulfur containing fuel. - Same - Formation of ammonium sulfates.
Maintenance	Periodic inspection for evidence of significant deposition, fouling, or corrosion.	To anticipate the development of gas side corrosion.	All root causes.

Table 3-12
Overview of Actions to Avoid Acid Dewpoint Corrosion

Mechanism: Acid Dewpoint Corrosion

Brief Description of Mechanism: Condensation of sulfuric acid and water vapor on metal surfaces with temperatures below the acid dewpoint, leading to corrosion of the metal surface.

General Approaches to Avoidance: Operating changes to increase tube temperatures; reduce fuel sulfur levels, upgraded material, water wash and protect tubing during shutdowns.

Unit Life Cycle Stage	Actions	Objective	Relevant Root Cause
Owner Specification	Require consideration of acid dewpoint corrosion as part of the design package. Provide a listing of anticipated fuels so that cold end temperatures can be calculated.	Require a clear understanding of conditions, which can lead to acid dewpoint corrosion and potentially susceptible locations.	Tube temperatures below the condensation point.
Design	- Evaluate whether cold end metal temperatures, in conjunction with expected level of contaminants and tube alloys used, are likely to result in significant deposition and corrosion problem. (Sec. 6.4) - Design to provide increased feedwater inlet temperatures by supplemental heating.	- To determine potential for acid dewpoint corrosion. - To provide for option to avoid low tube temperatures.	- Tube temperatures below the condensation point. - Same.
Fabrication/Erection	None		
Commissioning	- Evaluate back end gas dewpoint temperature. (Sec. 10.7) - Verify feedwater inlet temperatures for various modes of operation.	- To determine whether there is likely to be a developing corrosion problem. - To ensure that the feedwater inlet temperature exceeds the dewpoint temperature.	- Tube temperatures below the condensation point. - Tube temperatures below the condensation point.
Operations	- Reduce oil firing. - Change oil to lower sulfur content. - Maintain HRSG feedwater inlet temperatures above the gas dewpoint	- To minimize the sulfur level and lower the acid dewpoint. - Same - To maintain tube temperatures above the dewpoint and lessen condensation on susceptible surfaces.	- Fuel choice and operating conditions affect the acid dewpoint. - Same. - Operating conditions.

Damage Avoidance by Mechanism

Table 3-12
Overview of Actions to Avoid Acid Dewpoint Corrosion (continued)

Unit Life Cycle Stage	Actions	Objective	Relevant Root Cause
Maintenance	• Periodic inspection for evidence of significant fin, under-fin or tube corrosion (visual and ultrasonic thickness testing). • Periodic water washing to remove deposits (if oil-firing) and application of corrosion inhibitor during shutdowns.	• Detect incipient damage • Prevent buildup of potentially corrosive species.	• All root causes. • Tube temperatures below the condensation point during shutdowns.

Table 3-13
Overview of Actions to Avoid Stress Corrosion Cracking

Mechanism: Stress Corrosion Cracking

Brief Description of Mechanism: Cracking in a susceptible material by simultaneous exposure to stress and an aggressive aqueous environment. Can occur from tube ID or OD.

General Approaches to Avoidance: Control of environmental influences (preferred), reduction of stresses (difficult), change to a less susceptible material.

Unit Life Cycle Stage	Actions	Objective	Relevant Root Cause
Owner Specification	Require consideration of stress corrosion cracking as part of the design package. (Sec. 6.4)	Require a clear understanding of conditions, which can lead to acid dewpoint corrosion and potentially susceptible locations.	Susceptible material, environment and stresses.
Design	- Design to keep applied stresses below the SCC threshold and also to minimize residual stresses, at locations such as bends, welds, supports, spacers or tube attachments that can be susceptible to SCC. - Design to avoid crevices (use full penetration welds, no tight, closely contacting surfaces between tubes and other tubes, seals, insulation, etc.) - Include SCC resistance and sensitization as factors governing material choice in susceptible locations. - Design to minimize periods of component wetness (stack dampers, economizer/feedwater heater bypass, water preheater/recirculation). (Sec. 6.4) - Develop proper chemical cleaning procedures. (Sec. 4.6, 5.10)	- To minimize local stresses. - To minimize locations where moisture and contaminants can accumulate. - To minimize, where possible, use of sensitized material. - To minimize moisture accumulation. - To avoid chemical cleaning errors.	- Locally high stresses. - Environment. - Sensitized material. - Environment. - Contamination in HRSG steam.
Fabrication/ Erection	- Minimize residual stresses such as present in bends, welds, supports, spacers or tube attachments can lead to SCC (normalizing bends, post weld stress relief, etc.). - Use proper weld procedures for all materials, with an awareness of residual stress levels. (Sec. 9.4) - Avoid heat treatment procedures that sensitize susceptible materials such as austenitic stainless steels	- To minimize local stresses. - To minimize local stresses. - To minimize extent of sensitized material.	- Locally high stresses. - Locally high stresses. - Sensitized material.

Table 3-13
Overview of Actions to Avoid Stress Corrosion Cracking (continued)

Unit Life Cycle Stage	Actions	Objective	Relevant Root Cause
Commissioning	• Monitor tube and gas temperatures and dewpoint to verify that moisture will not be present during operation. (Sec. 10.7) • Monitor and tune the CT and supplementary burners, SCR and CO catalyst. (Sec. 10.7) • Sample gas and fluidside scales/films at selected regions, which may be exposed to moisture. (Sec. 10.7) • Establish optimum chemistry, controls, instrumentation, procedures, and actions levels to minimize contaminant levels. Check for carryover from drums. (Sec. 10.6) • Establish optimum shutdown and layup procedures to minimize corrosion, leading to the transport of contaminants on startup. (Sec. 10.6) • Eliminate localized areas of overheating caused by firing auxiliary fuels and firing equipment (duct burners). (Sec. 10.7)	• To minimize moisture accumulation. • To minimize SCC-influencing contaminants (sulfur, ammonia, etc.). • To verify low sensitivity to SCC. • To control the level of impurities (such as chlorides) in the HRSG water and steam. • To minimize corrosion and subsequent transport of contaminant on startup. • To minimize sensitization of stainless steels.	• Environment. • Environment. • Environment. • Environment. • Environment. • Sensitized material.
Operations	• Ongoing gas and fluidside chemistry monitoring and control. Must include drum carryover. • Control condensation and HRSG tube atmosphere during shutdown.	• To maintain clean environment and minimize contaminants in steam tubing. • To maintain clean cycle chemistry on unit restart.	• Environment. • Contamination in HRSG steam.
Maintenance	• Utilize proper shutdown, venting/draining and layup practices. • Perform examinations during off-line periods for moisture accumulation. • Follow established and optimized chemical cleaning procedures to avoid chloride contamination. • Periodic visual examination for signs of missing supports, etc. that could lead to high residual stresses.	• To minimize periods of wetness. • To verify that pressure parts are properly dried and free of condensate. • To maintain clean cycle chemistry. • To identify locations where locally high stresses might eventually lead to SCC.	• Environment. • Environment. • Environment. • Locally high stresses.

Table 3-14
Overview of Actions to Avoid Short Term Overheating

Mechanism: Short Term Overheating

Brief Description of Mechanism: Exposure to temperatures well in excess of design or partial or full blockage of the tube circuit.

General Approaches to Avoidance: Limiting tube temperatures; upgrading materials to include more creep resistance; preventing excessive exfoliation

Unit Life Cycle Stage	Actions	Objective	Relevant Root Cause
Owner Specification	Requirement for design basis life assessment of all steam cooled tubing.	To ensure an adequate design lifetime for creep damage in SH/RH tubes.	Excessive gas/tube temperatures.
Design	- Design of supplementary burners and related control system. (Sec. 6.2) - Design details with inside diameter changes and bend designs that minimize the potential for blockages. - Design adequate drains for SH/RH and appropriate startup/shutdown procedures. (Sec. 4.3, 7.7)	- To avoid higher than anticipated gas/tube temperatures from overfiring, control malfunction. - To minimize potential for blockages. - To ensure that all condensate formed during shutdown is removed prior to startup.	- Excessive gas/tube temperatures. - Tube blockages (by exfoliated oxides). - Tube blockages (by condensate).
Fabrication/Erection	Installation of thermocouples to verify design basis gas, steam and tube metal temperatures. (Sec. 6.3, 10.2)	To confirm that actual temperatures are within appropriate range to achieve design lifetime.	Excessive gas/tube temperatures.
Commissioning	Performance of tests during commissioning to verify that the design basis gas, steam and tube metal temperatures were conservatively estimated for all of the anticipated operating scenarios (e.g., full load, low load, with supplementary burners in operation, trips with rapid restarts, normal starts, fast starts, etc.). (Sec. 10.2, 10.3)	To confirm that actual temperatures are within appropriate range to achieve design lifetime.	Excessive gas/tube temperatures.
Operations	- Operating procedures, training, and monitoring practices/systems. - Establish optimum shutdown and layup procedures. - Confirm that combustion conditions are within design parameters.	- To ensure that design basis temperatures are not exceeded. - To ensure that condensate does not accumulate at the bottom of SH/RH loops or bends. - To avoid overheating by excessive gas temperatures, periodic overfiring, or uneven firing of supplemental burners.	- Excessive tube/gas temperatures. - Tube blockages (by condensate). - Excessive tube/gas temperatures.

Damage Avoidance by Mechanism

Table 3-14
Overview of Actions to Avoid Short Term Overheating (continued)

Unit Life Cycle Stage	Actions	Objective	Relevant Root Cause
Maintenance	• Follow established and optimized chemical cleaning procedures.	• To ensure that adequate flushing occurs following cleaning to remove all cleaning fluid, oxide scale, and chemical cleaning residue.	• Tube blockages.

Table 3-15
Overview of Actions to Avoid Longterm Overheating

Mechanism: Longterm Overheating

Brief Description of Mechanism: The accumulation of creep damage by exposure to temperatures at or somewhat above design levels.

General Approaches to Avoidance: Measurement of internal oxide scale thickness, comprehensive life assessment; limiting tube temperatures; upgrading materials to include more creep resistance

Unit Life Cycle Stage	Actions	Objective	Relevant Root Cause
Owner Specification	Requirement for design basis life assessment of all steam cooled tubing as described in "Design" above.	To ensure an adequate design lifetime for creep damage in SH/RH tubes.	Excessive tube temperatures.
Design	Design basis life assessment of all steam cooled tubing including: (i) an estimate of the steam, gas, and midwall temperature as a function of the gas-touched length, (ii) design temperature of each section of unique tubing, (iii) an appropriate allowance for steam and gas-side wall loss, (iv) an estimated cumulative damage fraction at the end of the anticipated life of the HRSG. The calculations above should produce estimated cumulative damage fractions less than 0.75 for the critical location of each unique section of tubing. (Chap. 4, 7)	To ensure an adequate design lifetime for creep damage in SH/RH tubes.	Excessive tube temperatures.
Fabrication/ Erection	Installation of thermocouples to verify design basis gas, steam and tube metal temperatures. (Sec. 6.3, 10.2)	To confirm that actual temperatures are within appropriate range to achieve design lifetime.	Excessive tube temperatures.
Commissioning	Performance of tests during commissioning to verify that the design basis gas, steam and tube metal temperatures were conservatively estimated for all of the anticipated operating scenarios (e.g., full load, low load, with supplementary burners in operation, trips with rapid restarts, normal starts, fast starts, etc.). (Sec. 10.2, 10.3)	To confirm that actual temperatures are within appropriate range to achieve design lifetime.	Excessive tube temperatures.

Table 3-15
Overview of Actions to Avoid Longterm Overheating (continued)

Unit Life Cycle Stage	Actions	Objective	Relevant Root Cause
Operations	- Operating procedures, training, and monitoring practices/systems. - Confirm that combustion conditions are within design parameters.	- To ensure that design basis temperatures are not exceeded. - To avoid overheating by excessive gas temperatures, periodic overfiring, or uneven firing of supplemental burners.	- Excessive tube temperatures. - Excessive tube temperatures.
Maintenance	- Periodic examinations of internal oxide scale and wall thickness through the life of the HRSG. - Selective tube sampling. - Visual examination for gas laning and tube misalignment; confirmation with thermocouple data or steamside scale surveys.	- To ensure that the design basis wall loss rates and metal temperatures are not being exceeded. - To metallurgically characterize tube condition and assess remaining life. - To look for local hot spots and areas of high heat transfer.	- Excessive tube temperatures. - Excessive tube temperatures. - Excessive tube temperatures.

Table 3-16
Overview of Actions to Avoid Thermal Quenching-Induced Fracture

Mechanism: Thermal Quenching-Induced Fracture

Brief Description of Mechanism: Gross “off-design” events/transients resulting in rapid thermal quenching and overload failures, primarily at tube-to-header connections.

General Approaches to Avoidance: Correct design deficiencies, faulty control logic, equipment malfunctions and/or damaging operating practices to prevent the occurrence of “off-design” events/transients.

Unit Life Cycle Stage	Actions	Objective	Relevant Root Cause
Owner Specification	Require consideration of the potential for thermal quenching as part of the design package.	Require a clear understanding of conditions, which can lead to thermal quenching.	“Off-design” events/transients.
Design	- Proper design of attemperation, valve and drain systems, including operational and control logic. (Sec. 4.5, 7.7) - Optimize the design of tube-to-header welds (geometry, size and strength). (Sec. 7.9)	- To prevent inadvertent flooding of hot tubes with saturated or subcooled liquid. - To provide maximum resistance to fracture if thermal quenching occurs.	- Design/control deficiencies. “Off-design” events/transients.
Fabrication/ Erection	Ensure that all tube-to-header welds conform to the design requirements. (Sec. 7.16)	To provide maximum resistance to fracture if thermal quenching occurs.	“Off-design” events/transients.
Commissioning	Provide experienced operators during commissioning.	To prevent actions which lead to inadvertent thermal quenching.	Operating practices.
Operations	Ensure proper operating procedures, training, and practices.	To prevent the introduction of water into hot tube bundles and thermal quenching.	Operating practices.
Maintenance	Periodic inspection and maintenance of mechanical components (linkages, valves, etc.).	Prevent mechanical failures, which can result in thermal quenching.	Equipment malfunctions.

4

DESIGN: UNIT CHARACTERISTICS

4.1 Overview of this Chapter

This is first of five chapters that relate to activities conducted during the design phase of the combined cycle unit that will influence the longterm durability of the HRSG. By appropriate design and operation of the combined cycle generating unit (CCGU) as a whole, and of the HRSG in particular, large HRSGs can be capable of a lifetime of daily cycling service.

This chapter looks specifically at overall unit characteristics and sets the stage for more detailed examination of specific design aspects. This chapter addresses: operating flexibility (Section 4.2), designing detailed startup, shutdown, and operating procedures (Section 4.3), some issues pertaining to vertical versus horizontal gas path units (Section 4.4), turbine exhaust characteristics – effects on HRSG reliability (Section 4.5), and allowance for maintenance activities in the overall unit design (Section 4.6).

4.2 Operating Flexibility Issues

Action 4.2a: *Design HRSG and key auxiliaries for cyclic operation of the HRSG.*

Action 4.2b: *Specify, early in the design process, annual operating transients for the unit.*

Rationale: *Stresses and cycle 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. Including explicit design to allow for these conditions is fundamental to minimizing damage.*

Potential HRSG Damage: *Essentially every HRSG damage mechanism is exacerbated by cyclic operation either directly by cyclic stresses, or indirectly through the increased difficulty in controlling key cycle chemistry parameters.*

4.2.1 Introduction

Many CCGUs were originally specified assuming base load operation and accordingly designed to accommodate only a limited number of shutdown-startup cycles. However, quite early in the unit life, some CCGUs have been switched to cyclic operation to reflect power market realities. Since the end of the 1990s, several factors collectively have stimulated widespread interest in combined cycle plant capable of very flexible operations. These factors include: (i) progress with deregulation towards a competitive electricity generation industry, (ii) the growing

proportion of total generation produced from gas fired combined cycle installations, and (iii) the anticipated demand-driven escalation in gas fuel prices from increased utilization of gas for electricity generation.

Many owners now anticipate that in future there will be periods when electricity demand is low overnight, and other times when power purchase prices will not recover the gas fuel cost. Thus, the profitability of combined cycle installations will in the future be significantly enhanced by shutting them down overnight and at other times when electricity demand and available power purchase prices are low, provided that cycling the units off and on load does not (i) impair reliability, (ii) incur large unforeseen repair and replacement costs, or (iii) increase the risk of long outages for premature replacement of failed major components.

Operating flexibility is the ability to match the output generated at any instant by the combined cycle unit to that required for the most economical dispatch, and to do so with predictable and acceptable rates of expenditure of design lives of the various critical components of the unit. The operational flexibility and reliability of any particular CCGU is determined by the ease and repeatability by which the unit controls can maneuver the unit during startups and shutdowns without expending excessive life.

Units not designed for cycling tolerance can quickly accumulate damage by a number of chemistry- and stress-related damage types. It is significantly less expensive and less disruptive to design-in features tolerant of cycling operation, and make them part of the original construction, rather than retrofit the needed changes after several years of operation.

In general, insignificant thermal fatigue damage is caused to any components in the combined cycle unit during load swings between 50% of the combustion turbine (CT) output and baseload because HP and hot reheat (HRH) steam temperatures remain constant at CT outputs above about 40 to 50%. However, transiently high, predominantly thermally-induced, inelastic strains occur during heating and cooling of critical pressure components of the HRSG in very localized positions when the unit moves through lower CT outputs. These transients are most severe during startup and shutdown of the unit. Likewise, the risk of a temporarily corrosive environment in HRSG economizers and evaporators caused by deviations from the optimum water chemistry is potentially greatest during shutdowns and startup of the HRSG. Therefore the medium to longterm reliability and durability of the HRSG is determined, not by the relatively benign conditions it experiences during on load operation, but by the conditions that critical components of the HRSG are subjected to during startups and shutdowns.

The operational flexibility of the HRSG is maximized by understanding the conditions that give rise to potential damage mechanisms and then designing the HRSG, the CT combustion control systems, and the key auxiliary systems, to minimize the thermally-induced stresses in the more vulnerable HRSG components, and by engineering the methods of operation for coordinated CCGU shutdowns and startups to mitigate the most damaging thermal transients. To this end, it is important to emphasize that the CT exhaust gas temperature characteristics during all startups, load transients and shutdowns substantially impact on the operational flexibility of the CCGU. CT exhaust temperatures also impact the rate of fatigue life expenditure in the HP superheater, reheater and HP steam drum of the HRSG and steam turbine high temperature parts. The importance of correctly specifying the requirements of CT combustion control systems to

mitigate the damaging effects of unnecessarily severe changes in gas and steam temperatures during startup are discussed in Section 4.5.

It is evident from the failures that many designs of HRSGs have been based on past practices developed for HRSGs with significantly lower design temperatures, pressures and steam flow rates. In these cases, little or no consideration may have been given during design to the impact of significant increases in physical size, design temperature, and design pressure on thermally induced cyclic stresses and cyclic lives of more critical parts of the new design of HRSG,

The planned operation of the unit is a critical factor to be established before the procurement process, as it will drive many major design choices within the HRSG and for key auxiliaries. This should include, as a minimum, specification of the number of starts (cold, warm and hot), ramp rates, shutdowns and cooling procedures, steam turbine warm-up procedures, and part load operation. Table 4-1 indicates two alternative samples of CCGU transients that might be specified for design of the HRSG and other equipment. One example is for a CCGU expected to operate predominantly as a baseload unit for most of its 30 year design life. The second example is typical of a CCGU predicted to operate for about two-thirds of its 30 year life as a regularly cycling unit.

Table 4-1
Sample Unit Number of Transients for Design Purposes

Predicted Operating Regime	Predominantly baseload with continuous operation until later years of life		Regular Cycling Service for an average of 8 months per year	
	Average Annual	Cycles in 30 Year Life	Average Annual	Cycles in 30 Year Life
Cold start from ambient temperature after normal shutdown	5	150	5	150
“Cool” HRSG start following recommended normal shutdown, and offload from Friday evening until Monday morning	6 to 7	200	33	1,000
Warm start after normal shutdown, and offload for 36 hours	8 to 9	250	10	300
Hot starts following normal shutdown, and offload overnight	16 to 17	500	167	5,000
Trips followed by restart within 2 hours	8 to 9	250	8 to 9	250
Forced cool shutdowns followed by a cold start from ambient	5	150	5	150
Total shutdown/startup cycles for design		1,500		6,850

4.2.2 Designing for Cyclic Operation

Throughout the 1990s, the majority of the larger capacity, more efficient combined cycle plants were installed with expectations by the owner of a lifetime of baseload or continuous operation and only occasional planned shutdowns and startups. Then, the dominant concerns of the

majority of purchasers of HRSGs were to obtain lowest installed cost and maximum output and fuel efficiency from the CCGU. In many cases, little or no attention was given to cyclic life consumption in the HRSGs, either by the suppliers or purchasers, and the HRSG was assumed to be capable of accommodating with impunity whatever conditions were imposed on it during combined cycle unit startups and shutdowns. Indeed, many purchasers' specifications for the HRSG demanded that the HRSG accept, without damage, whatever conditions were imposed during startups and shutdowns of the combustion turbine and combined cycle unit, a requirement that is impossible to achieve.

In some cases, fatigue failures have occurred in HRSG superheater and economizer tubes after of-the-order-of only 10^2 unit startup–shutdown cycles. Other HRSGs that may not yet have experienced failures also have features that develop thermally induced cyclic stresses of unknown, but presumably lower, magnitude. However, in order to extend cyclic life from 10^2 to 10^3 cycles, the absolute minimum lifetime number of shutdown-startup cycles to allow for a predominantly baseload plant, the thermally induced cyclic strain range must be reduced by a factor of at least 2. To extend cyclic life from 10^2 to 6×10^4 cycles, and thus to accommodate 200 shutdown-startups cycles per year, the strain range must be reduced by a factor of between 3 and 4. Thus, it is likely that failures initiated by high cyclic stresses in those designs of HRSGs that have similar thermally restrictive design concepts and details, or are operated by similar inappropriate methods during shutdowns and startups, will become more frequent and widespread as HRSGs accumulate more shutdown/startup cycles.

Design weaknesses in the HRSG can be eliminated by adopting alternative HRSG design arrangements that do not develop significant thermally-induced stresses. Wherever the HRSG utilizes design concepts and details that can cause cyclic thermally induced stresses, it is essential that the peak cyclic stresses in critical pressure parts be quantified by (i) simplified analytical models which contain sufficient conservatism to ensure peak thermal stresses are not underestimated, or (ii) by more sophisticated finite element thermal-mechanical analytical models that do not need to include large margins to account for modeling inaccuracies. To have credibility, it is essential that thermal-mechanical analyses are based on realistic tube-to-tube and tube-to-header transient temperature differences measured on similar designs of HRSG. During commissioning of the CCGU, the transient temperature differences assumed for thermal-mechanical analysis should be verified by installation of temporary thermocouples and measurement of tube and header temperature transients during shutdowns and startups from different initial HRSG conditions. This issue is discussed in Chapter 10.

The keys to being able to perform extensive two shift cycling operation, involving several thousand CT/HRSG block overnight and weekend shutdown/restart cycles, without premature fatigue-related failures in the HRSG are discussed throughout this document. A few key points to be remembered are:

- Limit the thickness of HRSG headers that are subjected to rapid changes in internal fluid temperature during startups and shutdowns in the HP superheater, reheater and preheater/LP economizers by appropriate dimensional design and material selection (Section 7.4).
- Design HRSG with concepts and details that minimize thermal stresses in tubes and interconnecting pipes during startups and shutdowns. (Chapter 7).

- Design the CT to provide the lowest possible exhaust gas temperature at minimum CT output, and with facility to control CT exhaust gas temperature to a ramp rate selected by the DCS during startups and shutdowns, (Section 4.5)
- Design HRSG to minimize gas leakage and heat loss when shutdown, to maintain the HP drum and superheater at the highest possible temperature prior to the next startup.
- Utilize shutdown procedures that bottle up the HRSG HP section at close to the design maximum, so that the HP drum and superheater are both at the highest possible metal temperature prior to the next startup, (Section 4.3.2)
- Utilize the DCS to select and simultaneously control steam temperature and pressure ramp rates during startups and shutdowns to match the most restrictive allowable ramp rates in the critical HRSG and steam turbine components determined from the continuously measured condition of each critical component (Section 4.3.2).

4.2.3 Operating Flexibility of HRSGs Is Important Even for Predominantly Baseload Operating Regimes

The thermal gradients and stresses experienced in the more critically stressed parts of the HP superheater, reheater and HP steam drum of the HRSG during a few hundred cold startup/normal shutdown cycles and trip-very hot restart cycles can, depending on their thickness and the rate of change in fluid temperature imposed on these components during startups and shutdowns, consume a substantial portion of the cyclic life of those components. This is true even when the optimum HRSG design and methods of combined cycle unit operation are followed.

The thermal stresses developed in the HP steam drum during starts from low pressure can be managed by performing an initial heat soak by holding for a time period at a low pressure appropriate for the thickness of the HP drum. After the heat soak, ramping up the saturation temperature can proceed at a rate also dictated by the drum thickness. However, if the HP superheater or reheater headers are thick, then they may consume most of their creep fatigue life during a few hundred cold starts and trip-restarts, leaving little or no creep fatigue life for occasional warm or hot starts. The influence of header thickness and of heating and cooling rates on cyclic life expenditure rates, and also on tube-to-bulk header temperature differences, are issues discussed in Section 7.4.

CT trips from above about 40% load are very damaging to the lower header of the HP superheater, especially so if the unit is restarted within 1 to 2 hours of the trip. Following a CT trip subcooled condensate is formed in the finned superheater tubes after the gas turbine exhaust temperature drops below the HP saturation temperature. This causes a transiently large temperature difference between the tubes and bulk mean header temperature, which develops a high bending stress at the toe of the weld attaching the tube to the header. It also causes a severe quench cooling of the tube holes and header bore, which develops very high thermal stresses at the intersection of the tube holes with the header bore, and which eventually initiates cracks that grow radially around the tube holes into the tube hole and header bore.

The magnitude of cyclic life expended per trip/restart event is strongly influenced by the thickness of the header, but to give a perspective to the potential severity, a single trip from

above 50% CT output can consume of the order of 1% of the creep fatigue life of a typical thicker design of lower header of the outlet panel of the HP superheater. For thinner lower headers, the life expenditure caused by trips is significantly lower. The impact of header thickness on life consumption in the lower HP superheater header during rapid CT shutdowns is discussed in Section 7.4.

Thus, even for predominantly baseload service, the thickness of critical HP superheater headers needs to be appropriately limited. So too must some of the other design concepts and details discussed in Chapter 7 be incorporated on units expected to perform only occasional starts.

4.3 Designing Detailed Startup, Shutdown, and Operating Procedures

Action 4.3a: Develop detailed integrated unit startup, shutdown and operating procedures early in the design process, to be refined and confirmed during commissioning and operation.

Action 4.3b: Design appropriate hardware and controls required to ensure appropriate ability to achieve the developed operating procedures.

Rationale: Stresses and cycle 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. Including explicit design to allow for these conditions is fundamental to minimizing damage.

Potential HRSG Damage: Nearly every damage mechanism type, particularly thermal fatigue, creep fatigue, deposits, corrosion fatigue, underdeposit corrosion mechanisms, pitting, gas side corrosion, and acid dewpoint corrosion.

The purchaser should, early in the design process, require submittal of the draft operating procedures, defining how the operation of CT, HRSG, steam turbine and key auxiliaries will be integrated during startups and shutdowns. Further, the resulting steam and feedwater conditions transients that will be imposed on the critical parts of HRSG and steam turbine should also be specified. This preliminary design of the planned integrated CCGU operating procedures must be performed at the outset of design, as it forms the basis for calculation of the resultant thermal stresses and cyclic life determination for HRSG and steam turbine components.

Where the results of these calculations indicate that some components in the HRSG do not meet the specified life, or that to do so the duration of startups must be extended beyond the time limits permitted for out-of-compliance operation of the plant with air permit limits, then the HRSG design must be changed to improve its operational flexibility. Thus, development of the preliminary integrated operating procedures and the performance of the calculations to determine the consequent cyclic lives of HRSG components must be completed before HRSG materials are procured.

Methods of operation widely used for startup and shutdown have been developed to mitigate thermal stresses in the CT and steam turbine, but often have given little or no attention to the damaging conditions imposed on critical parts of the HRSG. This viewpoint has sometimes been justified by three lines of reasoning:

- First is the argument that prematurely distressed sections of HRSGs can be replaced at little cost. However, relatively simple additions and adjustments to widely used operating procedures can be developed that will considerably increase the durability and longterm reliability of those HRSG components. Furthermore, while the cost of procuring a new HP superheater or reheater module may be perceived to be “small”, what is often overlooked is that the lost generation opportunity may far exceed the basic cost of the replacement module. Required dismantling of other equipment to remove and install a new module may also be significant.
- Second, there has been resistance to modifications to combined cycle procedures because they may result in small adjustments to the proportion of the time the CT emissions exceed the permitted limit for continuous operation.
- Third, there has been a perception that operating procedures used during occasional shutdowns and startups on combined cycle installations that normally operate continuously, and which have experienced no HTF to date, gives assurance that HTF will not become a major problem later after the HRSG has accumulated more shutdown/startup cycles. The perception is not well founded. For the sections of the superheater and reheater that operate at higher temperatures, the probability of failures involving the interaction of creep and thermally induced fatigue increases as the number of shutdown/startup cycles and also operating hours on load accumulate.

When developing CT/CCGU operating methods for startup and shutdown, it is important to understand the different mechanisms that are potentially damaging to the HRSG, and the sensitivity of the peak thermal-mechanical stresses developed in the HRSG to alternative methods of startup and shutdown. The determination of the sequence of events and the dynamic conditions during transients is crucially important to the minimization of fatigue related damage in the CT, steam turbine and in various sections of the HRSG, including the HP superheater, steam drum and evaporator, the reheater, and the feedwater preheater/LP economizer.

CT/HRSG unit startups can also increase the potential for corrosion damage to tubes by various mechanisms, including; flow-accelerated corrosion in IP and LP evaporator tubes and riser pipes and in economizers tubes; corrosion fatigue; pitting corrosion inside economizer and evaporator tubes; deposition of dosing chemicals inside economizer tubes; external corrosion on the lowest temperature economizer. Appropriate operating practices are required to quickly restore optimum feedwater chemistry conditions during startups and to avoid operating conditions in evaporators and economizers that are conducive to one or more corrosion mechanisms.

Few combined cycle projects give adequate attention to the engineering of coordinated startups, and in many cases these are worked out in the field by an *ad hoc* group of commissioning engineers for the various equipment. None of these people can be expected to be well versed in the impact of alternative methods of operation on transient thermal stresses and thermal fatigue related the HRSG and other equipment. Their primary goal is usually to get the plant into operation and handed over to the purchaser as quickly as possible. It is rare that any precautionary advice is given on the correct methods for normal shutdowns and, as a consequence, many combined cycle units are unnecessarily rapidly consuming the limited cyclic life of their superheater headers.

Design: Unit Characteristics

The speed with which each CT/HRSG can be safely started without excessive life expenditure is strongly influenced by the initial temperature of the HP steam drum and HP superheater headers. During short duration offload periods, the HP superheater cools to close to HP saturation temperature. Thus to minimize the duration of startups, the procedures used for shutdown must ensure that the HP pressure is raised during the shutdown to close to its design maximum and the HRSG then bottled up to minimize the heat loss and rate of pressure decay in the HP section of the HRSG during the offload period. Design improvements that should be considered to minimize the rate of pressure decay in the HP section while the CT/HRSG is off-load, include:

- Installation of stack dampers.
- Insulation of the stack below the stack damper.
- Installation of duplicate motor operated isolation valves on all steam and feedwater connections to the HP and IP/reheater sections of the HRSG, arranged for automated sequenced operation by the DCS to maintain tight isolation during offload periods by at least one of each pair of valves.
- For units expected to start relatively quickly after shutdown periods longer than a weekend, use of sparging steam to maintain the HP drum, and thus the HP section of the HRSG, slightly above atmospheric pressure. This will reduce the time required for heat soaking the HRSG before steam conditions are suitable for rolling the steam turbine. Note, however, that large quantities of auxiliary steam are required to maintain the pressure above atmospheric in the HP section of the HRSG.

For rapid startups, it is essential to have auxiliary steam to raise condenser vacuum before CT ignition occurs in order to permit use of the HP and HRH bypass systems to control the HP and HRH pressures shortly after HP steam generation commences. Early use of the bypasses is also essential to establish cooling flows through the HP superheater and reheater tubes 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.

The reliability of the HP and HRH bypass/steam dump systems is important because the CT/HRSGs cannot be started without these systems. The experience internationally with bypass/steam dump systems has been extremely diverse. Some extensively cycled units have few or no problems with their bypass systems and consistently achieve stable control of steam conditions. Others have many problems, with failed components and erratic, unreliable, control of steam conditions during dumping. This is often because the importance of reliable performance from the bypass systems and the severity of the thermal and mechanical duties imposed by these high energy systems on control valves, attenuators, pipes, and condenser by large rapid changes in steam flows, pressures and temperatures have been underestimated.

For units intended for cycling operation, it is particularly important that the quality of the system design and the selection of key components is appropriate to the arduous duty imposed on them each time a CT/HRSG is started and again each time it is shut down. In order to be capable of controlling the HP pressure to the optimum low value for initial heat soaking of the HP drum during cold and cool warm starts, the volumetric capacity of the HP bypass system may need to

be somewhat larger than required to pass the design 100% steam flow at design maximum HP pressure.

It is also important to automate the DCS selection and control of the CT exhaust gas temperature setpoint and of the HP and HRH bypass valve and steam turbine HP and IP control valve inlet pressure control setpoints during CT/HRSG startups and shutdowns. This will ensure that steam temperature and pressure ramps are continuously matched to the most restrictive of the critical components of the HRSG and steam turbine, based on continuously measured conditions in those critical components. This issue is further discussed in Section 10.5.

Even for completed units, the utilization of operating procedures that soften the more severe transient temperature differences developed in the HRSG during shutdowns and startups are crucially important. This is true even for installations that perform only a few starts per year.

The contents of this section primarily address to combined cycle plants employing larger capacity combustion turbines of the F and G class, or equivalent.

The following subsections offer some design ideas for operating sequences for:

- Normal on load operation (Subsection 4.3.1)
- Normal shutdown for cycling service (Subsection 4.3.2)
- Shutdown sequence for “maintenance” access (Subsection 4.3.3)
- Cold startup (Subsection 4.3.4)
- Hot starts after an overnight offload (Subsection 4.3.5)
- Warm starts (Subsection 4.3.6)
- Hot start after trip (Subsection 4.3.7)

These design ideas are given as examples only and are not absolute. They take into consideration the HRSG; there are similar concerns with the steam turbine that should also be considered in order to match temperatures and thus reduce stresses.

Each of these types of cycles will produce a degree of life expenditure in tubes and thick section components. One result of the design phase should be the production of a table similar to that presented in Table 4-2 showing the calculated life expenditure for the various expected units cycles (an adjunct to those unit cycles defined in Table 4-1).

Table 4-2
Sample Summary Table for Life Expenditure (by component) Caused by Design Unit Cycles

Type of Thermal Cycle	Lifetime Number of Cycles by Type for HRSG Design (see Table 4-1)	Number of This Type of Cycle Alone to Exhaust 100% of Fatigue Life	Fraction of Cyclic Life Expended at End of Design Life by Each Type of Cycle
Normal shutdown -Cold start	n_1	N_1	$n_1 \div N_1$
Normal shutdown – “Cool” start	n_2	N_2	$n_2 \div N_2$
Normal shutdown – Warm start	n_3	N_3	$n_3 \div N_3$
Normal shutdown – Hot start	n_4	N_4	$n_4 \div N_4$
Trip – Hot restart	n_5	N_5	$n_5 \div N_5$
HRSG Maintenance shutdown – cold start	n_6	N_6	$n_6 \div N_6$

Design life criterion: $\Sigma (n_1 \div N_1 + n_2 \div N_2 + n_3 \div N_3 + n_4 \div N_4 + n_5 \div N_5 + n_6 \div N_6) \leq 1.0$
(parts < 427°C (800°F)) or ≤ 0.12 (parts > 427°C (800°F))
See Sections 7.3.2, 7.3.3, and 7.4.

Notes:

- Normal shutdown = overnight or weekend scheduled off-load period.
- Cold startup = startup from ambient metal temperatures (following a weekend or maintenance shutdown, unless some pressure has been maintained).
- Warm/hot start = startup following an overnight 6 to 12 hour shutdown (HRSG pressure at startup will control the time required to start and will be dependent on the shutdown time and pressure “tightness” of the system).
- Maintenance shutdown = shutdown performed at the most rapid rate of cooling possible without producing excessive damage to the CCGU components.

4.3.1 Design of Procedures for Normal on Load Operation

Once the CT/HRSG has been established on load within the normally permissible range of CT operation from about 50% (sometimes higher) up to baseload, the HP and reheat steam remains continuously near its design maximum temperature and pressures range between 50% and 100% of design pressure. As a result, there are few potential life-consuming thermal-mechanical mechanisms in the HRSG, unless the particular design of HRSG has undesirable design features. Thus, no restrictions need to be imposed on the rate of change in CT load between approximately 40% and 100%.

Depending on the design specification for the HRSG, the HRSG may impose a floor to the HP pressure, below which operation is not recommended. On CCGUs with two or more CT/HRSG trains, HP and HRH pressures may have to be elevated by operating the steam turbine and/or HP

and HRH bypass systems in inlet pressure control mode to maintain the HRSG HP and HRH steam pressures at or above the permitted pressure versus steam flow limits.

4.3.2 Design of Procedures for Normal Shutdown for Cycling Service

Critical to the life of upper and lower headers of the HP superheater, and to a lesser extent the HP drum, is how the method of coordinated combined cycle unit operation is “engineered” for the normal shutdown of each CT/HRSG in the combined cycle unit.

A normal shutdown is an overnight Sunday or weekend scheduled off load period. The normal shutdown is doubly influential to the life expenditure in the HP superheater because not only does it have substantial impact on the magnitude of the tensile stresses developed during the cooling part of the thermal cycle, but it also determines whether the next startup will be a hot, warm or cold startup depending on how much heat is preserved in the HRSG when it is shutdown and boxed up, thus the magnitude of the compressive stresses during the heating part of the cycle

Key objectives of the normal shutdown are to:

- Complete the shutdown and box up the HRSG with the HP drum pressure close to its design maximum so that the HP pressure remains as high as possible at the next startup. The rate of decay in HP pressure varies widely and is strongly influenced by how well tight isolation is maintained on all steam and water isolation points in the HP and HRH sections. Poor isolation on the HP bypass valve, which is usually the only single isolation point, is particularly influential to the HP pressure decay rate. HRSGs with very tight isolation can maintain HP pressure after an overnight shutdown and still have a small positive HP pressure after a weekend shutdown. Similar HRSGs with poor isolation on HP drains, HP bypass HP steam and HP feedwater may have very little pressure in the HP drum after an overnight shutdown and be at atmospheric pressure after 15 to 20 hours.
- Gently steam cool the superheater headers down to the CT minimum exhaust gas temperature by controlling the rate of deloading of the CT during the latter stages of deloading below 30 to 45% load (depending on CT type and ambient conditions), when the CT exhaust gas temperature begins to fall below about 593°C (1100°F) to reduce CT exhaust gas temperature at a predetermined rate to its minimum value at CT full speed no-load, (FSNL), Figure 4-6. By this means, the lower headers are cooled by steam, progressively lowered, temperature rate close to the saturation temperature. Then, when condensation occurs during deceleration of the CT or spin cools after shutdown, the thermal shock to the lower headers is quite moderate. If, as is common operating practice, the CT is shutdown rapidly from about 50% load then the superheater headers remain close to maximum operating temperature, and then when subcooled condensate runs out of tubes into the headers it causes severe quench cooling of the headers and a large tube-to-header temperature difference, and rapidly consumes creep-fatigue life.
- Transfer HP and hot reheat (HRH) steam from the steam turbine to the HP bypass and HRH steam dump systems when steam temperatures begin to fall significantly with falling CT exhaust gas temperatures. This occurs at loads below about 30 to 45%, so as to maintain the

shut down steam turbine as hot as possible and thereby minimize the duration of the subsequent startup.

An example normal shutdown procedure that accomplishes the objectives listed above is presented in Appendix A.

4.3.3 Design of Procedures for Shutdown Sequence for “Maintenance” Access

When the CT/HRSG is being shutdown for maintenance on the CT or HRSG, the normal shutdown procedure can be modified to permit earlier access to the CT or HRSG. A common practice to accelerate the cooldown of the CT for combustion and hot gas inspections is to run the CT continuously at purge speed immediately after it has been shutdown to force cool the CT. This practice can be harmful to the HRSG HP drum and superheater. The objective is to cool the HRSG as quickly as possible without causing undue thermal stress in order to give the earliest access to the HRSG. At the same time, another objective is to permit extended operation of the CT at purge cool to give earliest access to the CT for inspections.

An example maintenance shutdown procedure that accomplishes the objectives listed above without excessive damage to the HRSG pressure parts is presented in Appendix A.

4.3.4 Design of Procedures for a Cold Startup

Cold starts from ambient metal temperatures cause considerably more thermal fatigue life consumption in HP superheater headers and HP steam drum, (and to the turbine rotors and casings and to the turbine inlet valve chests), than hot starts. This is because the initial heating is by condensation at the inner steam-swept surfaces, which occurs at very high heat transfer rates. During condensation heating, the rate of heat transfer from steam to the inner surfaces considerably exceeds the rate of heat conduction away from the inner surface through the thickness of the materials. Thus, when heating is by condensation, the inner surface material of all components in contact with a replenished supply of steam are quickly heated to close to saturation temperature while the temperature of the bulk of the material thickness increases relatively slowly. Cold starts also transiently develop very high tube-to-header temperature differences in the HP superheater and reheaters. This occurs because the uncooled finned tubes closely follow the rapid increase in gas temperature before the bulk header temperature is significantly increased.

The initial thermal stress peak is caused by condensation of steam at atmospheric pressure, that quickly raises the inner surface temperature towards 100°C (212°F), while the bulk mean temperature remains close to ambient temperature and cannot be prevented (except by boxing up the HRSG HP section with high pressure at shutdown and minimizing heat loss throughout the weekend off load period). However, the heat input during CT acceleration raises the HP pressure and saturation temperature, so that by the time the CT is at FSNL, the HP saturation temperature may be between 121 and 150°C (~250 to 300°F), depending on the CT startup duration to FSNL.

Starts after a weekend shutdown will be cold starts for the HRSG because there will be little or no pressure in the HP drum. If, however, the HP drum and superheater metal temperatures can be kept close to 100°C (212°F), then the restart is a less severe “cold” start because there is less condensation heating and a somewhat smaller difference between the CT exhaust temperature at minimum load and the wall temperatures of HP drum and superheater header. Furthermore, the steam turbine rotors will remain much warmer. A startup sequence optimized for “cool” starts after a weekend shutdown will be shorter than a cold start with metals at ambient temperature.

The CT should remain at FSNL or minimum nominal load with lowest available CT exhaust temperature of 315 to 382°C (600 to 720°F), depending on the type of CT, until the peak difference between rotor surface and rotor mean temperatures has past, which may require a further 15 to 20 minutes at FSNL from rolling the steam turbine. Then, CT load can be raised such that CT exhaust temperature is ramped up at a predetermined rate acceptable to both the steam turbine and HRSG.

4.3.5 Design of Procedures for Hot Starts after an Overnight Offload

Typically, the duration of overnight shutdowns on cycled units ranges between 6 and 12 hours. Provided the shutdown was normal, the steam turbine rotor temperature can be predicted quite accurately as a function of the offload period.

This is not the case with the HRSG. The HP drum pressure prior to the restart could range from relatively high to nearly ambient after an overnight shutdown, depending on (i) what the HP pressure was when shutdown was completed, (ii) how much leakage there is from drains, steam and feedwater isolation valves, and the HP bypass valve (which does not have double isolation), (iii) drum blowdowns, (iv) whether there is a stack damper and stack insulation, (v) the prevailing ambient temperature, etc., The HP section of the HRSG between the HRSG gas inlet and HP evaporator tends to cool over the first few hours of the shutdown close to the HP drum saturation temperature. Thus, at startup, HP superheater header temperatures are close to the HP saturation temperature.

There is no clear discontinuity to draw a sharp distinction at some HP pressure between warm and hot starts for the HRSG and no good reason for doing so, because the procedures to be followed for hot and warm starts are in essence the same. Only the duration of the start will change as a function of the HP pressure prior to the start because the HP superheater header must be heated from the HP saturation temperature before the start.

In addition, for equivalent fatigue life expenditure, as the HP pressure before the start gets lower, and the total change in temperature during the startup increases, the allowable temperature change rate for the HP superheater header must be reduced for equal fatigue life expenditure. For starts from higher pressure, the total change in the HP drum saturation temperature is relatively small and the time required for pressure raising is not on the critical time path. However, as initial HP pressure drops, the heating of the HP drum at its allowable rate may become a critical time path factor in the startup duration.

The other component to consider is the HP drum. As with the HP superheater header, the smaller the total change in the saturation temperature, the faster the allowable ramp rate.

An example hot start procedure that is designed to minimize HRSG pressure part damage is presented in Appendix A.

4.3.6 Design of Procedures for Warm Starts

Depending on the initial HP pressure, warm starts will often closely follow the sequence of a hot start, but with somewhat lower steam temperature ramp rates. As the initial pressure before startup is reduced, the allowable temperature transients for the HP drum become increasingly significant, introducing the need for a hold at some moderate HP pressure to heat soak the HP drum, which is important also for the HP superheater header. Thus to the lower end of the notional pressure range categorized as warm starts, the startup procedure becomes increasingly more like a cold startup procedure, but with significantly less hold time for heat soaking the HP drum from saturation temperature than required during a cold start from ambient temperature.

4.3.7 Design of Procedures for Hot Starts after a Unit Trip

Hot starts following trips generally follow the same procedure as for hot starts after overnight shutdowns. If the trip was from a CT load above 50%, then the HP pressure will be relatively high and the allowable HP drum transients will not become limiting. For an immediate restart within an hour or two of a trip from above 50% CT load, the temperature of the HP superheater headers will also be high and well above saturation temperature so that a high steam temperature ramp rate is acceptable. If the trip occurred during a startup before the steam temperature reached its normal maximum, the restart should resume the steam temperature and pressure ramps being followed before the trip.

The principle concern about restarts immediately after trips from load is that the prestart purge will cause severe quench cooling of the lower HP superheater headers and large header-to-tube temperature differences if the purge and restart are performed immediately. The lower header creep fatigue life expended by an immediate restart after a trip from CT load above about 40% can be very high because the lower headers are still near full temperature.

There are substantial improvements in creep fatigue life expenditure of the lower headers by delaying the restart for a few hours until the lower headers have cooled by convection to within 111°C (200°F) or less of the saturation temperature. The time required for the lower headers to cool is strongly influenced by the thickness of the lower HP superheater headers and is best determined by tests with thermocouples attached to the outer surface of the lower header of the highest temperature superheater panel.

4.4 Issues Pertaining to Horizontal Gas Path (HGP) Versus Vertical Gas Path (VGP) HRSGs

4.4.1 Horizontal Gas Path (HGP)/Vertical Tube HRSG

Large HRSGs of the horizontal gas path (HGP) type have many panels, (sometimes referred to as “harps” or “racks”), comprising one, two or three rows of straight vertical tubes welded either directly, or via small radius, acute bends to the same pair of upper and lower headers. These

HRSGs are sometimes referred to as natural circulation or “American” type of HRSGs. Water circulation in evaporators is induced by the density difference between water below the saturation temperature in the downcomer and the water/steam mixture in the evaporator tubes. Figure 4-1 shows a simplified diagram of a single pressure HGP; additional detail for a three pressure HGP design with reheat is shown in Figure 4-2.

4.4.2 Vertical Gas Path (VGP)/Horizontal Tube HRSG

VGP HRSGs have predominantly horizontal tubes and the gas rises vertically through the heating surface sections. VGPs are taller, top supported HRSGs sometimes referred to as the “European” type of HRSG. Until recent years, VGPs have generally been assisted circulation type, requiring pumps to circulate drum water during startup and to assist circulation of drum water through the evaporator tubes. More recently, designs of the VGP type of HRSG have been installed that utilize natural circulation in the HP evaporator during on load operation but may use smaller circulation pumps to establish circulation during startup.

Some older designs of VGP HRSG, used with smaller combustion turbines, had tubes in some heating sections arranged with a single horizontal pass across the HRSG duct and attached to inlet and outlet headers on opposite sides of the duct, which would no longer be considered acceptable. For installations with larger capacity CTs VGP HRSGs should have tubes of each heating section arranged with a minimum of two, and preferably three or more predominantly horizontal passes interconnected by return bends into a serpentine tube configuration between inlet and outlet headers.

Inlet and outlet headers can be located on opposite sides of the vertical duct or one above the other on the same side of the HRSG. Figure 4-3 shows a simplified assisted-circulation, horizontal tube, vertical gas path HRSG. A schematic diagram of a more complex arrangement consisting of multiple pressure loops is shown in Figure 4-4.

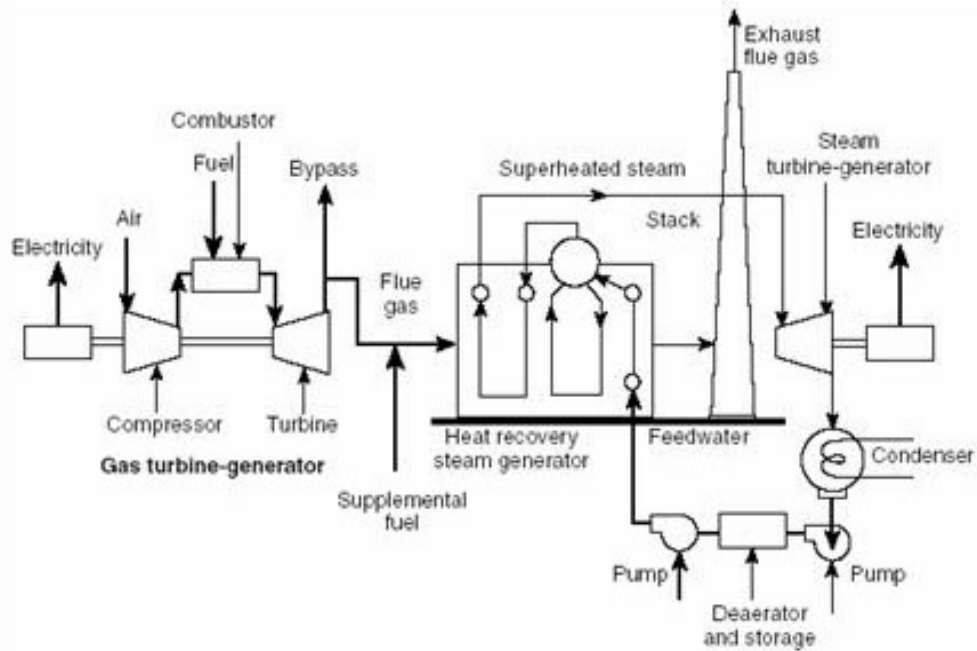


Figure 4-1
Simplified diagram of a single pressure HGP design.

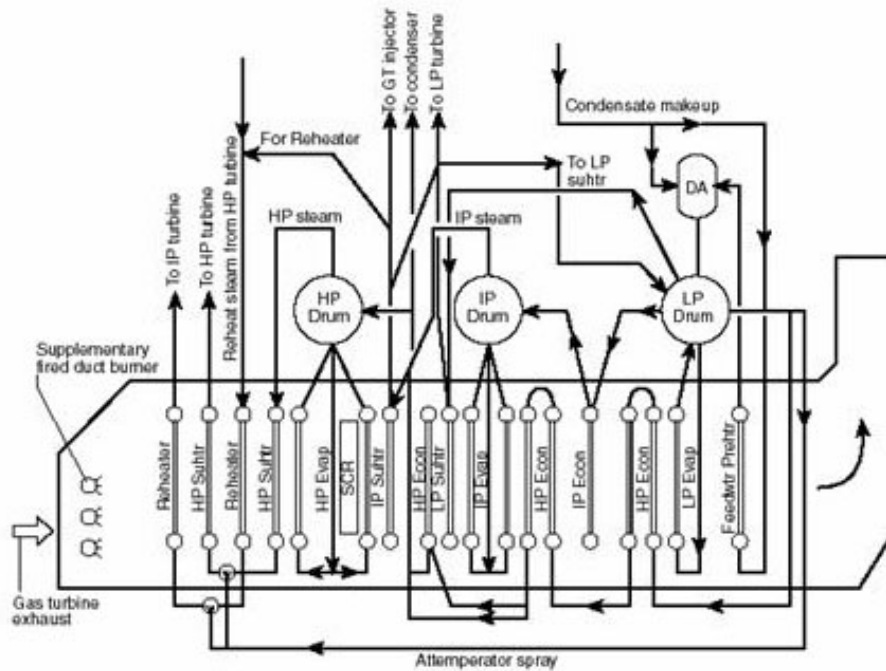


Figure 4-2
Three pressure HGP design with reheat.

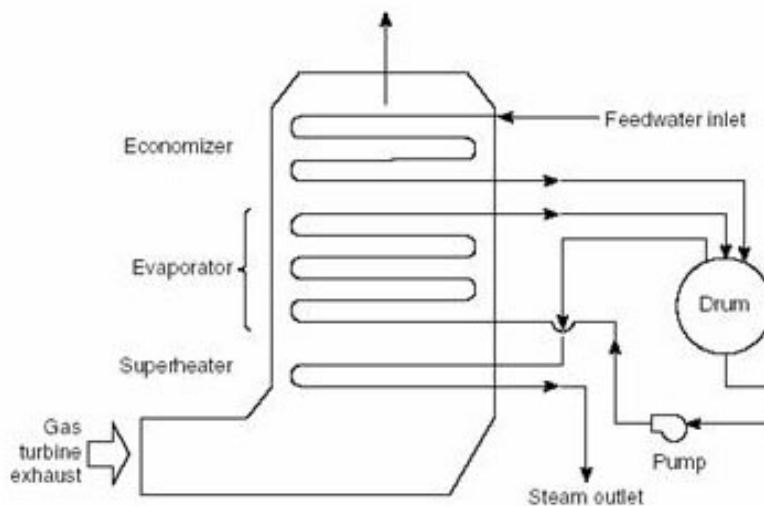


Figure 4-3
Simplified, assisted circulation, horizontal tubed, VGP HRSG.

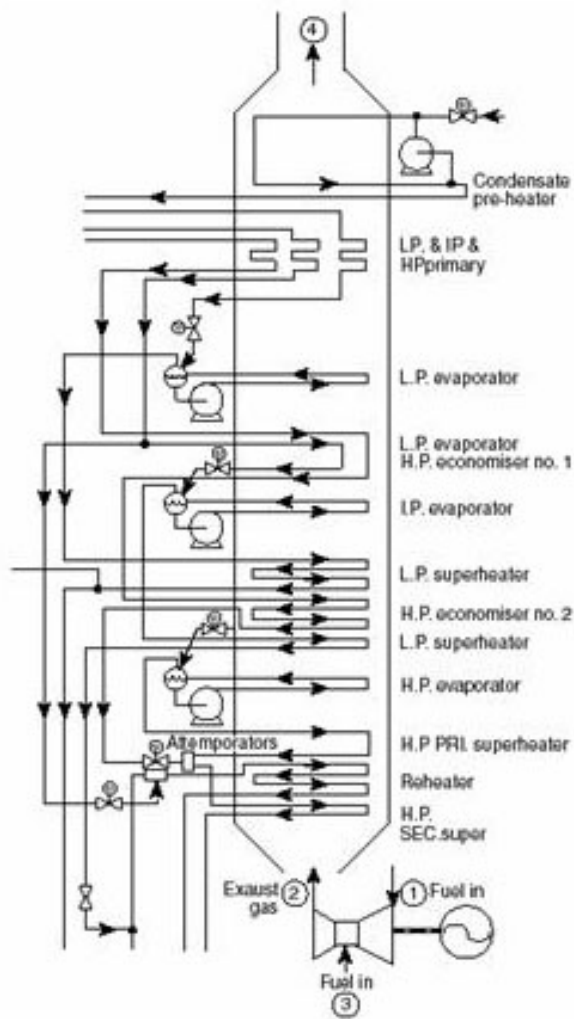


Figure 4-4
A more complex VGP HRSG.

The serpentine tube arrangement has greater tube flexibility to accommodate relatively large transient differences in temperature between tubes attached to the same pair of inlet and outlet headers than the considerably stiffer arrangement in the HGP type of HRSG. HGP designs are therefore significantly more vulnerable to high thermally induced stresses at tube attachments to the headers. Tubes in horizontal tube, vertical gas path HRSGs are typically smaller than vertically tubed HRSGs, and incorporate multiple uncooled tube supports to limit the magnitude of tube sag between supports. In order to ensure that tubes of the VGP HRSG experience innocuous thermally induced stresses, it is important to be assured that the method of support of the predominantly horizontal tubes will successfully allow the tubes to slide freely at the supports when expanding and contracting without developing significant axial forces in the tubes. Tubes supported on the fins are more prone to cumulative fin damage that leads to increased friction forces in the tubes. Support of tubes at unfinned sections of the tubes is more durable (see Figure 7-3).

The boiling process in horizontally tubed HRSGs is somewhat more complex than in vertically tubed units. There is a driving force tending to stratify the steam and water flows in the horizontal tubes (steam to the top of the tubes and water to the bottom). Return bends will modify this distribution somewhat.

4.5 Combustion Turbine Exhaust Characteristics – Effects on HRSG Reliability

Action 4.5a: *Understand that CT exhaust gas temperature characteristics have a significant impact on the cyclic life of tubes in the HP superheater and reheater.*

Rationale: *The role of large changes in gas temperatures can lead to significant pressure part damage.*

Potential HRSG damage: *Thermal fatigue, creep fatigue, possibly corrosion fatigue.*

The introduction of the F-class and equivalent large industrial combustion turbines has considerably increased both the steady state and dynamic conditions imposed on the HRSG. The pursuit of lower installed cost per MW has caused substantial escalation in CT exhaust gas mass flows. The drive towards higher combined cycle efficiencies to reduce fuel consumption costs has caused significant increases in CT exhaust gas temperatures from typically 593°C (1100°F) for E-class and equivalent CT technologies and up to about 649°C (1200°F) for F-class and equivalent CT technologies. Earlier combined cycle designs based on F-class CT technologies utilized two-pressure non-reheat cycles with HP steam temperature of 538°C (1000°F), but current combined cycle units are usually three-pressure reheat units with HP superheater and hot reheat steam temperatures of about 565°C (1,050°F).

Dry Low NO_x (DLN) combustion technology has also significantly increased the CT exhaust gas temperatures during startups and when the CT is held at its minimum output of about 5 to 10%, especially with those CT designs that startup in DLN mode and do not use diffusion combustion mode for startup and low load operation of the CT.

The significance of the differences in the exhaust gas characteristics of F-class and equivalent designs of CT to the HRSG and other CCGU plant during startups and shutdowns is discussed in Section 4.5.1 and during operation on load in Section 4.5.2.

4.5.1 Influence of CT Exhaust Characteristics During Startups and Shutdowns on HRSG Reliability

Action 4.5b: *Specify/ensure that the CT is capable of maintaining a moderate exhaust gas temperature, not more than about 380°C (716°F) and preferably lower, at minimum CT output after synchronizing.*

Rationale: *This will to limit the initial tube-to-header temperature difference at HP superheater and reheater headers before any steam flow can be initiated.*

Potential HRSG Damage: *Thermal fatigue and creep fatigue cracks at toe of tube attachment weld-to-header and/or at intersection of tube holes with bore of higher temperature headers.*

Action 4.5c: *Ensure that the CT is capable of controlling the rate of change in exhaust gas temperature, and thereby the steam temperature ramp rates, during startups and shutdowns to an operator- or DCS-selected ramp rate.*

Rationale: *The goal during startups is to match the rate of increase in HP and reheat steam temperatures to the requirements of steam turbine or HRSG HP superheater, whichever momentarily happens to be the more restrictive. CT exhaust gas temperature matching is also essential during normal shutdowns to lower the HP steam temperature at a controlled rate and gently steam cool the lower headers down close to the saturation temperature before completing the CT shutdown. This is done in order to prevent developing damaging thermal stresses at tube-to-header attachments and also in the headers at the surfaces of the tube holes.*

Potential HRSG Damage: *Thermal fatigue and creep fatigue cracks at toe of tube attachment weld-to-header and/or at intersection of tube holes with bore of higher temperature headers.*

The thin-walled finned tubes of the HP superheater and reheater tube rows most directly exposed to the gas exhausted by the CT closely follow the CT exhaust gas temperature. The headers to which the tubes are attached are located out of the gas stream. As a result, they are heated and cooled predominantly by the fluid in contact with the tube holes and the inner surface of the header at much lower rates of heat transfer (except during those periods when condensation heating or quench cooling by sub-cooled condensate occurs). The bulk mean wall temperature of the thicker-walled header is heated and cooled by conduction from the surfaces in contact with the fluid and responds to changes in gas, and thus steam, temperature changes at a much slower rate than do the tubes. Thus, rapid and large changes in CT exhaust gas temperature develop transiently high temperature differences between the tubes and headers, especially in the higher temperature sections of HP superheater and reheater.

When tubes are significantly hotter than the bulk mean temperature of the header to which they are rigidly attached, each tube is prevented from expanding radially from its axis for a transient period. As a consequence, each tube develops a thermal bending moment in the tube wall and a compressive stress around the circumference of the tube at the toe of the weld attached to the tube. Similarly, large negative temperature differences between the tube and header by condensate quench cooling shocks cause high thermal bending stresses at the toe of the tube-to-header weld that are tensile. Since the stress range of each of the two potentially severe transients is additive, it is particularly important to avoid both being applied to the same tube-to-header attachments.

The parameters that determine the tube-to-header temperature difference during startups are CT exhaust temperature at minimum CT load, and header thickness. The parameters that determine the negative tube-to-header difference in lower HP superheater heaters during shutdowns are the header temperature when the CT firing ceases and the HP saturation temperature at shutdown. The following paragraphs discuss the conditions that develop tube-to-header temperature differences and actions that should be implemented to minimize the fatigue damage caused by tube-to-header temperature differences.

During all CT startups, the CT exhaust temperature increases rapidly during acceleration and usually peaks at about 80% speed and then reduces during the final acceleration stage before falling back during synchronizing and adding the minimum CT output of about 5 to 10% for spinning reserve. The peak exhaust gas temperature varies for different CT designs and combustion systems, but for F-class and equivalents is usually between 510 to 565°C (950 to 1050°F) and has usually passed within 3 to 4 minutes of CT ignition and then falls quickly to a more moderate temperature. The typical CT exhaust gas temperature illustrated in Figure 4-5 indicates the temperature at spinning reserve is about 496°C (925°F), but this unit has an optional “exhaust temperature matching” upgrade that lowers the exhaust temperature to about 380°C (716°F) at spinning reserve output. This modification can have significant benefits.

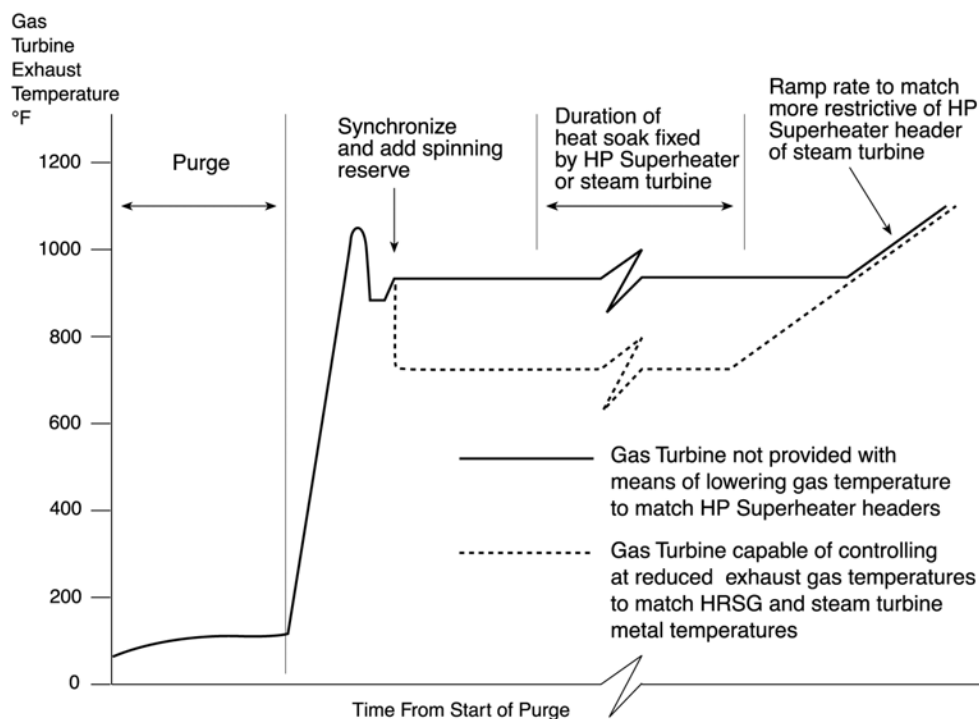


Figure 4-5
Typical CT exhaust gas temperature profile with and without exhaust temperature matching.

In Figure 7-12(b), for example, a cold start from ambient temperature of a different design of F-class CT, the peak exhaust gas temperature in a F-class unit is 510°C (950°F) and occurs about 3 minutes after ignition. The gas temperature then reduces to about 320°C (610°F) when at spinning reserve. Figure 7-12(b) also shows that the maximum tube temperature doesn't peak until about 7 to 8 minutes after CT ignition, as a result of the thermal inertia of the tube and fin material. At that time, the CT exhaust gas is falling towards the spinning reserve temperature so that the gas inlet row tubes peak at about 370°C (700°F) before reducing to gas temperature of 320°C (610°F) at spinning reserve. Thus during cold HRSG startups, the tubes will be heated to a temperature somewhat in excess of the exhaust gas temperature at spinning reserve output within 7 to 8 minutes of CT ignition.

During cold starts, there is no steam production or steam flow until about 10 minutes after ignition and therefore no cooling flow is possible through the tubes. The headers are heated by condensation at their inner surface, and by conduction from the thin tubes. The rate of increase in bulk mean temperature of the headers is strongly influenced by their thickness. By 7 to 8 minutes after CT ignition when the tubes have reached their peak temperature at the exhaust gas temperature at spinning reserve, the bulk temperature of the header may, depending on its thickness, be in the range of 46°C (115°F) for a thick header to 177°C (350°F) for a header less than 17 mm (0.67 in.) thick.

Thus, without the exhaust temperature matching option and an exhaust gas temperature at minimum load of 496°C (925°F), the tube-to-header peak temperature difference may be close to

388°C (700°F), which is unacceptable even for a baseloaded unit. With exhaust temperature matching, and gas temperature at minimum CT load of 380°C (716°F), the peak tube-to-header temperature difference with widely used header thickness may still exceed 305°C (550°F) during cold starts and thus poses a potential limitation for units intended for cycling service (Table 7-1). The lower CT exhaust gas temperature of 321°C (610°F) with the design of the CT in Figure 7-12(b) reduces the tube-to-header temperature difference during cold starts by about 56°C (100°F). This substantially reduces the risk of fatigue failures in the weld toe, provided also that the header thickness is moderate and the high temperature panels are of single-row tube type. The impact of the HP superheater header thickness, CT exhaust gas temperature at minimum load and the implications of more than one tube row per panel in the superheater or reheater are discussed in Section 7.4.

Even for CCGUs intended for continuous operation with only occasional cold starts, the exhaust gas temperature of 495°C (925°F) illustrated in Figure 4-5 is unacceptable, and installation of the exhaust temperature matching option is recommended to provide an exhaust gas temperature slightly above 370°C (700°F) at minimum CT load.

During shutdowns, it is equally important to be able to lower the CT exhaust gas temperature at a controlled ramp rate dictated by the thickness of the HP superheater headers down to a minimum exhaust gas temperature close to 370°C (700°F). This is necessary in order to lower the steam temperature at a rate that gently cools the lower headers close to the HP saturation temperature before the CT is shutdown. This avoids potentially severe quenching of the lower headers by condensate which forms in the tubes when the gas temperature falls below the saturation temperature either during the CT deceleration to turning gear or in the subsequent spin cool or purge. The widely used practice of fast deloading and shutdown of the CT, illustrated in Figure 4-6, leaves the headers close to their normal maximum operating temperature so that when condensation occurs during or shortly after CT shutdown, there is a large temperature difference between the condensate and the tubes and the header. This potentially severe thermal shock is avoided by an extended shutdown recommended for all normal shutdowns.

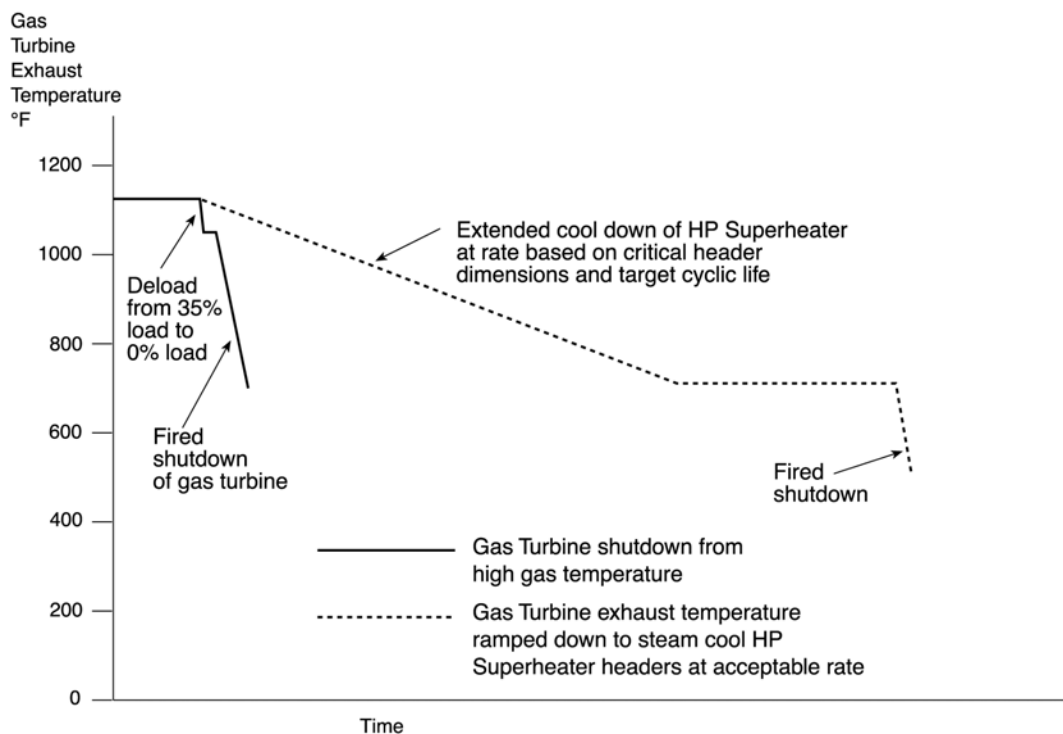


Figure 4-6

Typical CT exhaust gas temperature profile during fast deloading and shutdown and during extended shutdown to steam cool HP superheater headers.

4.5.2 Impact of CT Exhaust Characteristics During On Load Operation on Design and Reliability of the HRSG

Action 4.5d: *Design the position of the attemperator within the HP superheater to ensure that the steam condition after attemperation remains superheated when operating with the CT at part load and an exhaust gas temperature higher than at baseload.*

Rationale: *To avoid significant tube-to-tube temperature differences.*

Potential HRSG Damage: *Thermal fatigue at tube attachments to downstream headers.*

Overspraying to saturation temperature can cause significant tube-to-tube temperature differences in the downstream tube row, developing large forces and stresses in the tubes. HRSGs behind CTs with exhaust gas temperature characteristics that significantly raise the exhaust temperature to an isothermal limit as load is reduced from baseload require considerably higher attemperation flows when the CT is at part load than for CTs with a relatively constant exhaust gas temperature over the normal operating load range.

Action 4.5e: *Pick appropriate rate of change of CT output to limit rate of change in steam temperature at the outlet from the HP superheater attemperator.*

Rationale: Large, rapid change in steam temperature at the attemperator outlet develop high thermal stresses in the attemperator outlet pipe tee and in the inlet header to the downstream section of the HP superheater.

Potential HRSG Damage: Thermal fatigue caused by load-cycling operation.

For CTs, which operate in mid-output range with exhaust gas temperature at an isothermal ceiling, which is significantly higher than at baseload, it is important to restrict the maximum rate of change of CT output over this output range.

4.6 Design Allowance for Maintenance Activities

4.6.1 Access for Inspection, Cleaning, and Repair

Action 4.6a. Require design features that will allow for appropriate inspections, cleaning and repair access of HRSG pressure parts.

Rationale: Access to HRSG tubes and headers for condition assessment and/or repair is notoriously difficult. Design-in features to partially offset the typical constraints will be beneficial.

Potential HRSG Damage: This action is relevant to early detection and repair of damage from any failure mechanism. Proper repairs are appropriate to avoid secondary damage, or repeat failures in the same location as the original damage.

HRSGs are generally designed in a more compact fashion than conventional fossil fueled boilers. Consequently, the available space for performing inspections and easy access for maintenance is usually severely limited. Congestion is common in HRSGs, which generally restricts access for inspection and maintenance, Figure 4-7 illustrates the problem.

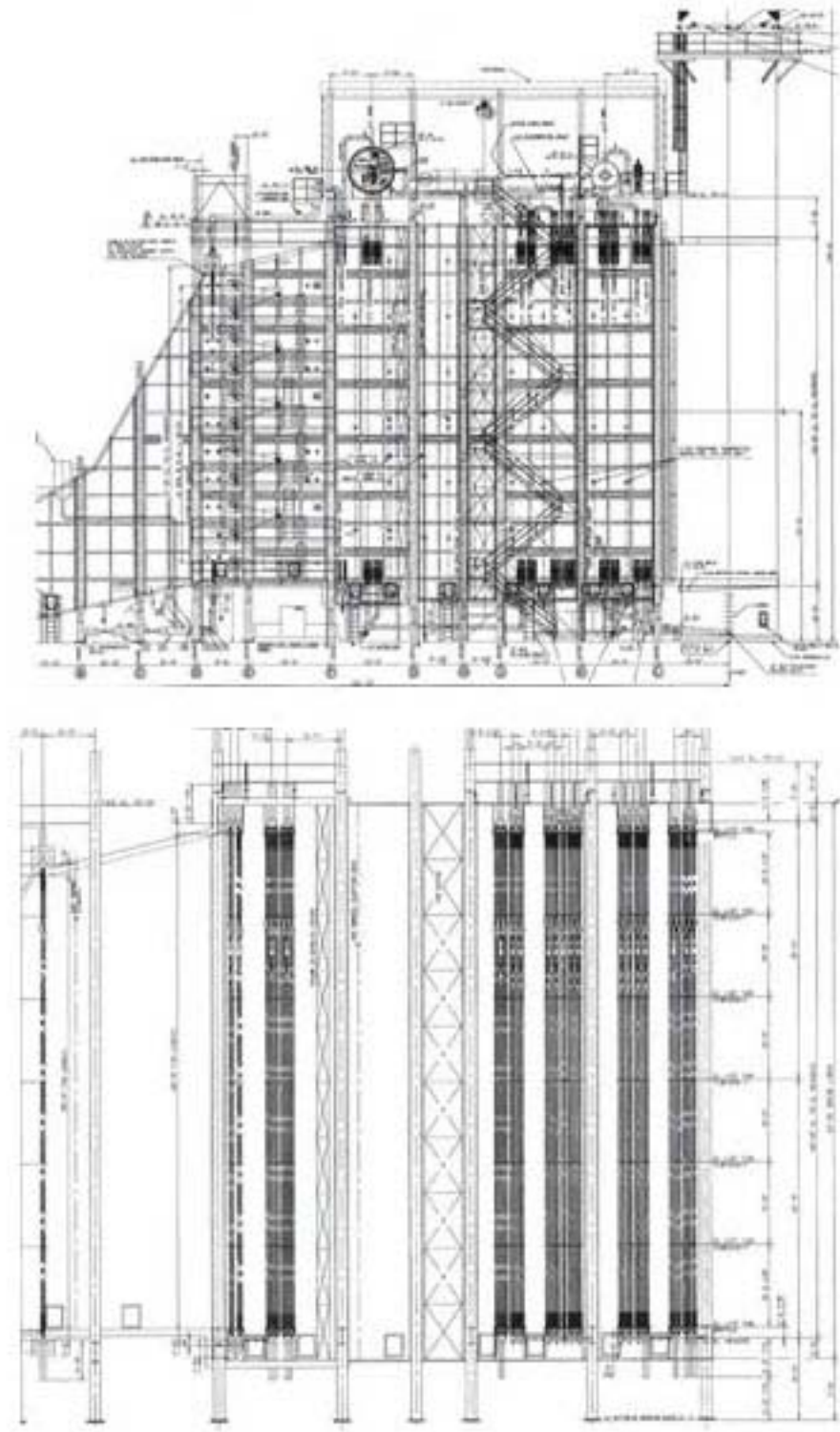


Figure 4-7
Illustrations of typical horizontal HRSG, depicting the close proximity of pressure parts.

Design: Unit Characteristics

Care must be taken during the design and specification stage to provide equipment owners with the ability to clean, inspect, repair, and replace pressure parts during the operating life of the HRSG. Chapter 9 on fabrication and construction, and Chapter 10 on commissioning provide examples of the types of inspections, and cleaning that will be required early in the life of the HRSG.

Good design practices with regard to access include:

- Consider leaving unfinned tubes in selected locations to increase the ease of future inspections. Locations should be chosen with an eye on potential tube failure mechanisms and an understanding of the likely operating conditions of tubes in susceptible locations.
- Design-in access provisions for inspection and repair of tube-to-header welds.
- Design-in access for internal inspection of headers and manifolds.
- Design-in access for replacement of SCR and CO catalysts.
- An access way should be provided between each HRSG module as a minimum. The accessways should permit access to superheater and reheater sections to permit field performance correction by baffling as needed. The accessways should permit inspection of feedwater preheater coils both upstream and downstream. Access doors should be provided on both sides of the accessways. The accessways between tube bundles should be a minimum of 760 mm (30 in.) clear to permit internal scaffolding.
- Access doors should be provided to all areas of ductwork and stacks for inspection and repairs.
- The minimum access door opening should be 450 x 600 mm (18 x 24 in.). Access doors should be pressure tight, constructed of steel plate with reinforcement and frames. Doors should be bolted to casing frames and should have gaskets, hinges and handles. Grab bars should be provided above access doors.
- Access doors should be provided on each side of the SCR and CO catalyst beds. Catalyst loading doors should be provided for catalyst loading and removal. Piping, structures and other components should not obstruct catalyst loading or door removal. Clearances should allow for external insulation.
- To enhance maintainability, manway access should be provided between each bundle to assure accessibility to the full faces of all tube bundles.
- All openings passing through the boiler wall should be gas-tight.
- The maximum tube bundle depth should be 18 tubes, so that any may be repaired by removing no more than eight other tube row sections.
- Access to operating platforms at drum level(s) including drum manways should be by stair tower. The stair tower should be arranged so that all sections are entered from the immediate landing of the previous section. Other platforms should have ladder access.

Finally, good design practice should be followed to ensure proper clearance between piping equipment and passageways for operation and maintenance. Proper space should be provided to service control valves and their operators.

4.6.2 Allowance for Chemical Cleaning

Action 4.6b. Require design features that will allow for adequate chemical cleaning.

Rationale: Pre-operational and operational cleaning will be required. Proper chemical cleaning, especially rinsing of all cleaned systems is critical to avoid damage to pressure parts and/or subsequent deposition in tubing.

Potential HRSG Damage: Underdeposit corrosion mechanisms, generalized corrosion.

Although use of modern manufacturing methods, in combination with well-planned component manufacturing, transportation and storage techniques and satisfactory construction practices offer the possibility of eliminating the need for preoperational cleaning, field experience has proven that this goal is rarely if ever realized. In view of this, the design should consider the need for preoperational chemical cleaning of the system. Also, periodic operational chemical cleaning of the high pressure evaporator circuit will be needed in most units. Other HRSG circuits and cycle components may also need to be operationally cleaned in some instances. Thus, it is most desirable to establish a design that will facilitate effective cleaning efforts. Aspects that need to be considered include the following.

- Drains: should be sized to ensure rapid (within 1-2 hours) filling and draining, this in order to minimize corrosion of base metal, maximize removal of undissolved solids and minimize rinsing and flushing requirements.
- Vents: should be sized and positioned to ensure reliable evacuation of gases from the component being cleaned, this to avoid formation of gas pockets that could prevent or restrict solvent circulation or movement.
- Chemical Cleaning Piping: generally, temporary piping is installed to meet the requirements of the cleaning process; permanent piping, occasionally installed on some conventional boiler units, would be of great benefit if engineered for the high pressure HRSG during the design stage.
- Steam and Water; the design should consider the need for steam and condensate or makeup purity water during cleanings and ensure that they can readily be supplied to the work area or, alternatively, that space is available to accommodate equipment such as package boilers and portable water treatment systems that may be needed during cleanings.
- Accessibility: As a minimum, the design should provide access to all HRSG circuits and components comprising the steam-water cycle of the unit. Workable space should be provided in which to prepare chemical cleaning solutions, inject them to the component to be cleaned, and remove and collect the resultant cleaning wastes for proper treatment and disposal. The design must allow for containment of any solvent leaks and spills that may occur during the cleaning process, such as from tube leaks within the HRSG.

4.6.3 Allowance for Water Washing Downstream of SCR Catalyst.

Floor drains for water washing downstream of SCR catalyst where the turbine exhaust gas (TEG) temperatures are 232°C (450°F) or below should be provided with collecting piping and valves at the HRSG sidewall. Other casing drains should have pipe caps. All casing drains should be accessible.

5

DESIGN: FLUID SIDE

5.1 Overview of this Chapter

This chapter examines key fluid side design issues that will influence the development of HRSG pressure part damage. The chapter is divided into two primary parts. The first part, Sections 5.2 through 5.10, covers a multiple of cycle chemistry issues as befits the central role that cycle chemistry plays in the longterm reliability of the HRSG.

The overall objective of HRSG cycle chemistry treatment is to minimize corrosion of, and deposition at, all surfaces in contact with water and steam. Effectively satisfying this objective requires careful interaction with the unit design, as well as operational requirements and restraints, and other factors that may influence the suitability of available treatment approaches.

The discussion of design phase cycle chemistry starts with sections on hardware and design choices that will precede the development of the optimal cycle chemistry. It then looks at optimum feedwater treatment and HRSG treatment for each pressure cycle. The concentration of effort during the initial and actual design phases needs to be on choosing:

- Makeup water source and makeup treatment (Section 5.3)
- Materials for the feedwater and evaporator circuits (Section 5.4)
- The importance of including a condensate polisher and/or leak tight condenser (Section 5.5)
- Other HRSG configuration issues (Section 5.6)
- The optimum feedwater (or pre-HRSG or pre-deaerator) treatment (Section 5.7)
- The optimum HRSG treatment for each pressure circuit (Section 5.8)
- Setting impurity targets and actions levels (Section 5.9)
- Ancillary design features to ensure overall optimum cycle chemistry – shutdown and layup facilities, air in-leakage control, and facilities for chemical cleaning (Section 5.10).

The discussion of design considerations of cycle chemistry then concludes with an additional short section summarizing specific cycle chemistry design considerations organized by individual HFT mechanisms (Section 5.11).

It should be noted that very important follow on actions to optimize and maintain cycle chemistry are also contained in Chapter 8 (Instrumentation and Controls), Chapter 9 (Fabrication and Construction) and Chapter 10 (Commissioning).

5.2 Introduction to HRSG Cycle Chemistry

Overall it is estimated that cycle chemistry influences over 50% (and perhaps as much as 70%) of the total lost generation costs, availability and performance losses in combined cycle units, making this topic very important to the overall reliability of the plant. It will allow organizations to “build the plant around the cycle chemistry”, rather than thinking about the chemistry once the plant is built. Currently as delineated in the HRSG Tube Failure (HTF) Manual [5-1], many of the most important causes of HRSG pressure part failure are influenced by the cycle chemistry, Table 5-1.

Table 5-1
Cycle Chemistry Influences on HTF Mechanisms [5-1]

Mechanism	Chemistry Influences
Flow-accelerated corrosion	Reducing chemistry conditions; alkalization of deposits
Hydrogen damage	Waterside deposits; low pH
Acid phosphate corrosion	Waterside deposits; deficient phosphate control
Caustic corrosion	Waterside deposits; high pH
Waterside deposits	Cycle chemistry not optimized
Corrosion fatigue	Cycle chemistry not optimized
Pitting	Shutdown; dissolved oxygen; low pH
Longterm overheating	Internal deposits
Short term overheating	Internal deposits
High temperature fireside corrosion	Internal deposits
Stress corrosion cracking	Carryover; steam contamination

Interim Cycle Chemistry Guidelines for Combined Cycle Heat Recovery Steam Generators (HRSGs) [5-2], published in November 1998, remains the only comprehensive cycle chemistry guideline for HRSG units in the world. It covers once-through and drum units, the five possible HRSG chemistry treatments (AVT, EPT, PT, CT and OT), the three possible HRSG feedwater treatments (AVT(O), AVT(R) and OT), and the necessary roadmaps to steer organizations to select the optimum treatments. Figures 5-1 and 5-2, from that document, provide overall roadmaps for optimizing feedwater (or pre-HRSG or pre-deaerator) treatment and HRSG treatment for each pressure cycle, respectively. They will be referred to throughout this chapter. The guideline remains the main resource for all stages of HRSG cycle chemistry optimization from design, through commissioning to operation. Incorrect choices have led to HTF in less than six months from initial operation [5-1].

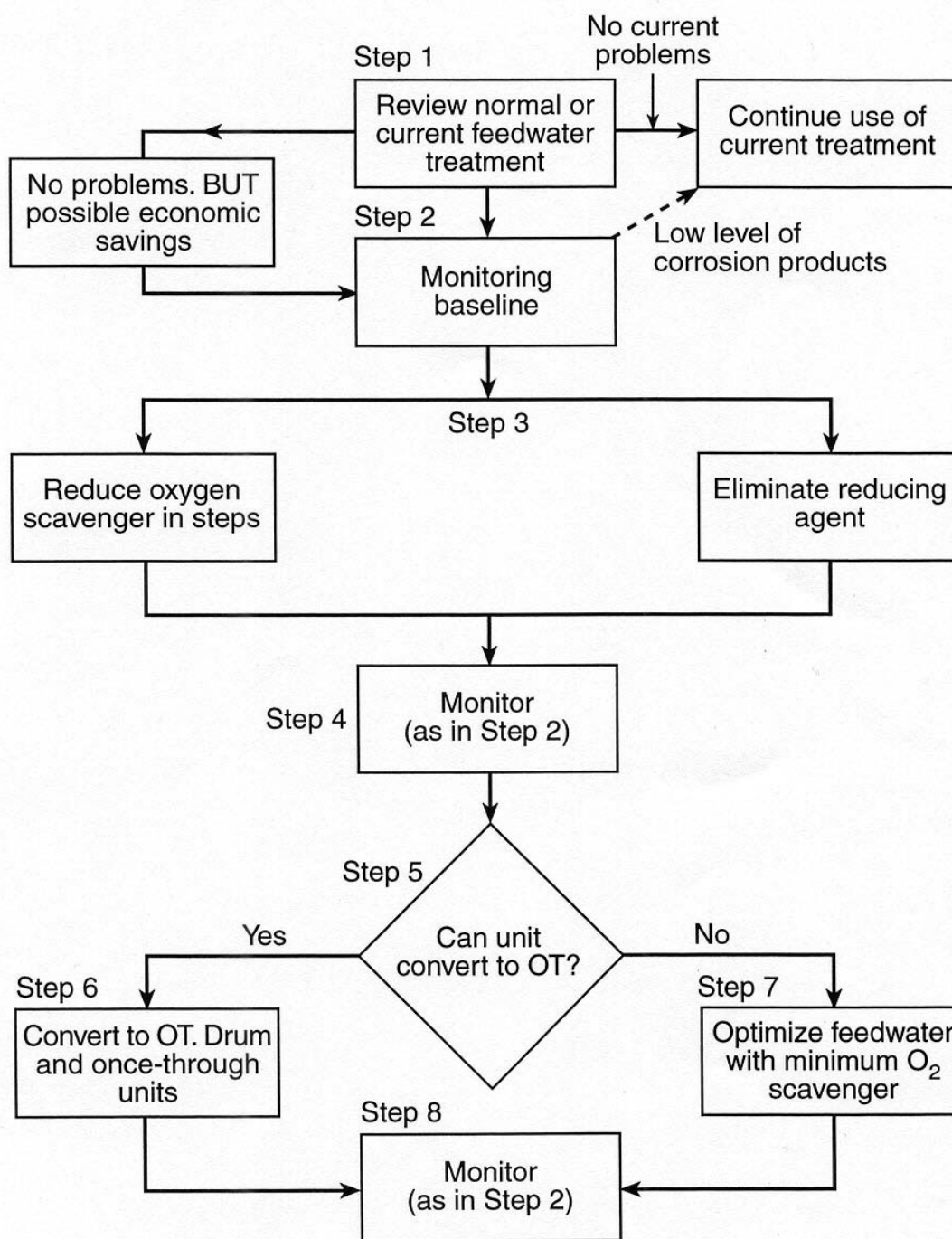


Figure 5-1
Roadmap for optimizing feedwater treatment for all-ferrous once-through and drum units.

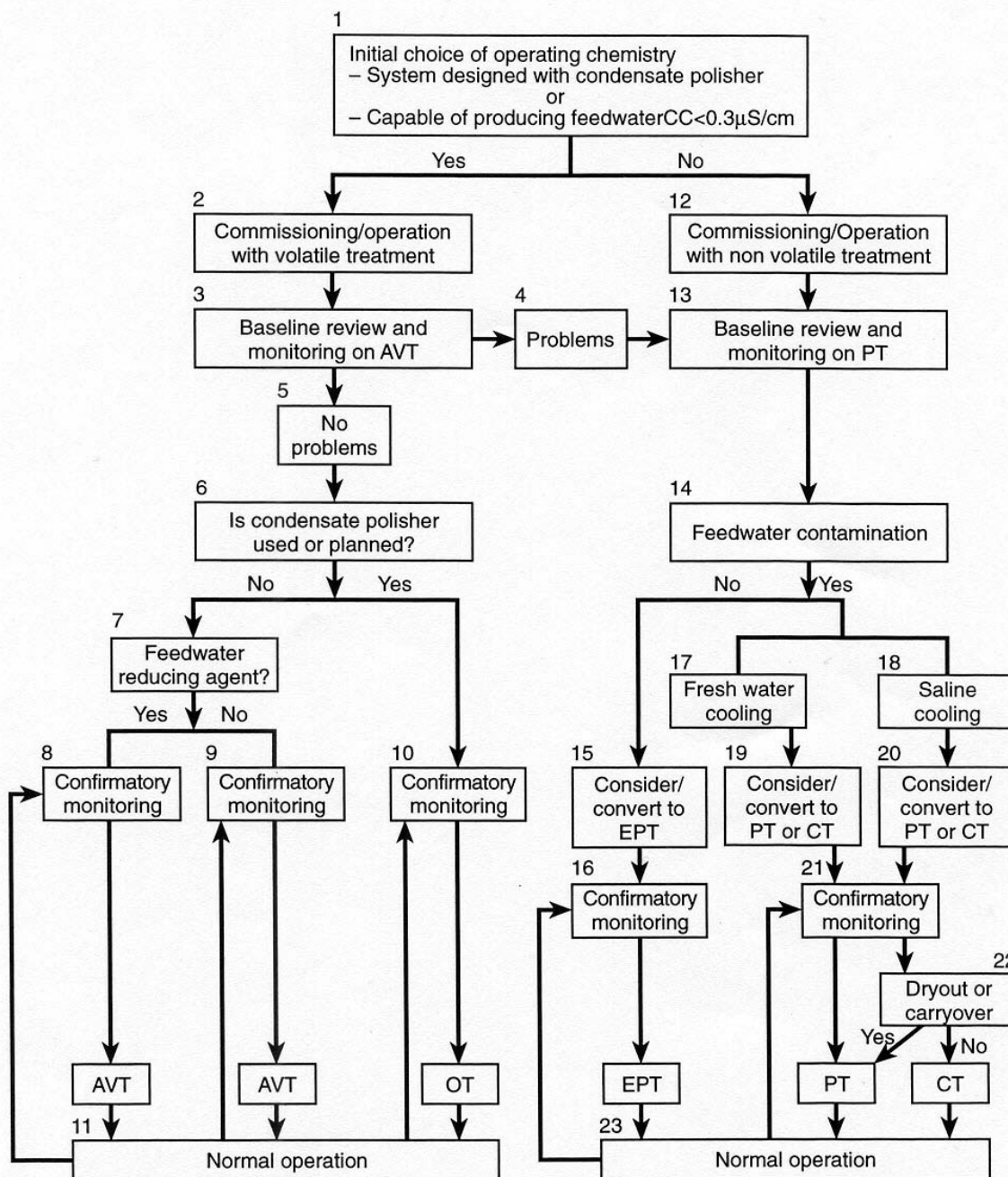


Figure 5-2
Roadmap for drum HRSG water treatment selection.

The purpose of the next eight sections of this chapter is to bring out those aspects of plant cycle chemistry design that need to be considered during the conceptual and actual unit design phase, to ensure optimum reliability once the plant becomes operational. To accomplish this, the experience developed in the HTF Manual [5-1] has been overlaid on the cycle chemistry guidelines.

5.3 Makeup Water Source and Makeup Treatment

Action 5.3. *Need specific design for makeup water treatment plant that is based on the characteristics of the water supply and the needs of the combined cycle unit, not arbitrary cost constraints.*

Rationale: *Properly specified, designed and operated makeup systems are integral to avoidance of corrosion and deposition activity on water and steam touched surfaces; further, utilization of high purity makeup water maximizes the ability of tools such as blowdown and condensate polishers to deal with contaminant ingress sources.*

Potential HRSG Damage: *All internal (waterside) corrosion mechanisms, including underdeposit mechanisms.*

A key consideration in cycle chemistry starts with a knowledge of makeup water and its purity. In the case of cogeneration facilities, makeup requirements for cycles with HRSGs can be significantly greater than the requirements for conventional cycles. Key questions to be answered during the design phase include:

- Will the makeup be from a single source or multiple sources?
- What percentage of the makeup will come from what sources?
- How much makeup water will be needed and for what purposes?
- Will this analysis indicate the need for a condensate polisher in addition to a properly specified and designed makeup treatment system?

Makeup requirements for cycles with HRSGs can be significantly greater than the requirements for conventional cycles, ranging from almost 0% to 100% of steam flow. Factors affecting makeup include:

- Type of cycle, especially the number, type and operating pressure of the individual evaporator circuits.
- Cogeneration requirements/quantity and purity of returned condensate. (Condensate purity also influences the need for inclusion of a condensate polisher in the design.)
- Necessity for water or steam injection into the combustion turbine for NO_x control (and/or to increase power output of the combustion turbine/generator).
- Anticipated (typical and maximum) blowdown and other cycle losses (leakage, steam seals, water and steam sampling, etc.).

Design: Fluid Side

The water purity required for these cycles depends upon several factors [5-2], such as:

- Requirements for water or steam injection for NO_x control.
- Attenuation water source and quantity.
- Amount of makeup in relation to condensate flow.
- Amount and purity of condensate return in relation to condensate flow.
- Design of HRSG (once-through or drum-type).

Even though the LP drum HRSGs may operate at relatively low pressures (as compared to conventional units) the above factors will almost always dictate that the makeup system furnish a final makeup water purity approaching (and preferably equaling) that produced from a mixed-bed unit. (A unit with a single low pressure evaporator circuit could perhaps be operated with softened water makeup; the content of this report is not intended to address combined cycle units of this type.) Once-through HRSGs circuits dictate that mixed-bed quality water be provided for makeup.

It should be understood that the importance of makeup purity control is particularly acute in units with high makeup requirements. Clearly, the influence of sodium or silica leakage on condensate, feedwater, and HRSG water chemistry will be more significant in cases where makeup represents more than 50% of feedwater flow than it will in instances where makeup is less than 10% of feedwater flow. Total organic carbon may be of special concern in units with high makeup requirements since ion exchange is less efficient in removal of organic impurities than in removing inorganics. Organic fouling of ion exchange resins reduces their exchange capacity and limits regeneration capabilities. Breakdown of organic impurities will result in creation of acetate and formate, which can depress HRSG water pH and increase cation conductivity levels in the cycle. Breakdown of chlorinated organics, if not removed by the makeup water treatment system, represent a potential source of chloride within the cycle.

5.4 Materials for the Feedwater and Evaporator Circuits

Action 5.4 Specify that all materials in the feedwater system are all-ferrous.

Rationale: Designs that specify all-ferrous materials can use water treatment approaches that are preferable to those that must be considered in units with non-ferrous alloys. Conventional fossil units that can employ these treatments achieve better availability, reliability and performance statistics than comparable units that include copper alloys and similar results are expected in combined cycle units.

Potential HRSG Damage: Waterside deposition and underdeposit corrosion mechanisms.

The materials in the feedwater must be all-ferrous and are usually, in the latest designs, carbon steel. Clearly no copper alloys should be included. The evaporator circuits should also be carbon steel with the exception of those areas (usually return bends) which should/can be of low chromium containing (1.25 to 2.5%Cr) materials to ensure that flow-accelerated corrosion (FAC) will not be able to occur. In making this choice, operators and designers alike should not be

lulled into the security of thinking that this will counteract FAC in its entirety throughout the feedwater, deaerator, drum and evaporator systems. That objective can only be accomplished by choosing initially, commissioning, and monitoring for, the optimum cycle chemistry in the unit.

The choice of all-ferrous materials, in combination with properly selected and optimized water treatments (see Reference 5-2) will minimize corrosion activity and subsequent corrosion product transport and deposition of iron oxides on heat transfer surfaces (particularly in the highest pressure evaporator circuit). As a result, the vulnerability of the unit to HRSG tube failures by underdeposit corrosion mechanisms is minimized (see Chapter 3 and Reference 5-1). Furthermore, the need to chemically clean evaporator circuits is minimized or eliminated entirely.

5.5 The Importance of a Condensate Polisher or Leak Tight Condenser

Action 5.5a *Specify, if at all possible, a condensate polisher.*

Action 5.5b *If a condenser is to be used, ensure that it is designed to be “leak tight” and constructed of titanium tubes for the best cycle chemistry performance.*

Rationale: *Contamination from water cooled condensers (and the failure to take appropriate corrective actions upon detection) is the root cause of numerous waterside and steamside damage mechanisms. Designs that include polishers and/or titanium condenser tubes represent sound investments that pay for themselves many times over in the course of the operating life of the unit.*

Potential HRSG Damage: *Waterside deposition, corrosion and cracking mechanisms.*

The question about including a condensate polisher or balancing condensate, feedwater and evaporator purity through appropriate choice of condenser materials, is admittedly contentious. It has not been a purely technical decision in the past. Although the EPRI HRSG Cycle Chemistry Guidelines [5-2] include the possibility of having a condensate polisher in the circuit for each of the five possible treatments, the actuality over the last 10 years has been very disappointing in that very few organizations have elected to specify a condensate polisher in their initial or conceptual proposals. Only a few operators with seawater cooling have made this election. Polishers have also been specified in some cogeneration projects, where the purity of condensate returns to the cycle was likely to be unacceptable due to contamination by dissolved solids and/or corrosion products.

Why is this disappointing? Requiring a low installed cost of a combined cycle HRSG is easily understood, although in the longterm it continues to be proved to be very short sighted. It is also clear that the manufacturers (or bid responders) will not under their own volition include a polisher in the design; in a very tight competitive situation, they will lose the job! However, it is very clear in conventional plants that the best operational performance is associated with units that have a condensate polisher [5-3]. EPRI's benchmarking of over a 100 units/plants clearly indicates that the units in the World Class category have polishers, all-ferrous feedwater systems, and operate with AVT(O) or OT.

Design: Fluid Side

The use of condensate polishing is rare for existing units featuring drum-type HRSGs. However, the dearth of condensate polishing on these existing units cannot be used as evidence that polishing would not improve water chemistry or that polishing might not even be required in certain circumstances.

Condensate polishing has proven to be cost justified for conventional drum-type units in recent EPRI studies based upon consideration of the following factors [5-4]:

- Mitigation of condenser leakage (especially on high solids cooling water such as from closed cycles or sea water)
- Improvement in startup time
- Reduction in HRSG blowdown
- Reduction in the need for chemical cleaning
- Reduction in HRSG tube failures

There is no reason to believe that the above considerations would not be equally applicable to drum-type HRSGs for combined-cycles or even simple cycles (with the exception of benefits attributable to condenser leakage).

For combined cycle units without condensate polishing the hold period waiting for steam quality acceptable to the ST is a critical path delay during cold, warm and hot starts, which significantly impacts ability to comply with air permit limits for out-of-compliance operation. Units with condensate polishers quickly and dependably obtain acceptable steam quality and then shutdown the polishers after about 30 minutes into the startup.

Condensate polishing is required for once-through HRSGs and for drum-type HRSGs operating on OT. An exception to this requirement has been taken in the latest advanced cycles that combine a drum-type and once-through HRSG in the same unit [5-5].

The once-through HRSG design installed in several locations in the US and Canada uses nonregenerable mixed bed polishers that have very low makeup requirements [5-6]. Condensate polisher resins are replaced when exhausted, and not regenerated. A full flow filter is placed downstream of the polisher. No chemical feed is used in the heat cycle, which essentially operates on OT.

It has become clear over the last 5-8 years (depending on geography) that a very “leak tight” condenser made with rolled and welded titanium tubes can also restrict contaminant ingress. In these cases, even without a condensate polisher, experience has indicated that it is relatively easy to consistently produce better than 0.2 $\mu\text{S}/\text{cm}$ cation conductivity feedwater. In these cases, the initial feedwater chemistry would be AVT(O). During the commissioning phase (see Chapter 10) and early operation the route started by Step 2 in Figure 5-2 would be followed.

Thus it is the job of the future operator to specify, and of the manufacturer or engineering company responsible for the conceptual design, and of the designer during to the initial and design phases, to ensure that at least one of these possibilities (condensate polisher and/or tight condenser) is chosen. In this way the concept of future reliability is then “designed” in.

The alternative is not attractive. This choice, if accepted by the team and delineated by the steps starting with Step 12 in Figure 5-2, immediately introduces the possibility of future failure and chemistry control problems. Thus, in this case, failure is “built in”.

Condensers may be water cooled or air cooled; both have been used. For the former, tube materials would be a function of type of raw water in the circulating water system and might include copper alloys, stainless steels, or titanium. To preclude copper deposition in the HRSG and steam turbine, recommendations for condenser tubes would include the use of stainless steels or titanium, as applicable. Higher iron levels are usually found in feedwater with air cooled condensers.

5.6 Other HRSG Configuration Issues

A multiplicity of HRSG designs and cycle configurations exist. In addition to the choice of a condensate polisher or condenser as discussed above, many other hardware choices will have a critical influence on the design of the HRSG cycle chemistry system. Some of those choices are:

- Single pressure, dual-pressure, and multi-pressure designs (Subsection 5.6.1)
- Water from the LP drum may feed the IP and HP circuits (Subsection 5.6.2)
- Water from the IP drum may feed the HP circuit (Subsection 5.6.2)
- Cascading blowdown may be practiced on multiple pressure HRSGs (Subsection 5.6.2)
- Deaeration may be performed in the feedwater or as part of the LP drum (Subsection 5.6.3)
- Feedwater may feed into a deaerator which then feeds all the pressure circuits (Subsection 5.6.3)
- Attemperation water may be taken from the LP drum or the feedwater system (Subsection 5.6.4)
- Feedwater heaters/preheaters may or may not be present (Subsection 5.6.5)

5.6.1 Chemistry Optimization Issues Relating to Single Pressure, Dual Pressure or Multi-Pressure Designs

Action 5.6a *Select initial chemistry for feedwater and evaporator water circuits in accordance with EPRI Guidelines [5-2], then verify and optimize the treatments during commissioning (Chapter 10).*

Rationale: *To avoid the chemistry related damage to HRSGs and steam turbines that has been experienced in early operation of many combined cycle units.*

Potential HRSG Damage: *Potential problems include pre-HRSG general corrosion and FAC, deposition in evaporators, underdeposit corrosion, and overheating damage.*

Design: Fluid Side

The feedwater treatment selection (see Section 5.7) must consider unit materials of construction and other factors as discussed throughout this report. Details are provided in the interim chemistry guidelines report [5-2].

5.6.2 Forward Feeds of LP Drum Water to the IP and HP Circuits or IP Drum to the HP Circuit and Cascading of Evaporator Blowdown to Lower Pressure Circuits.

Action 5.6b *Carefully consider the impacts of these design features, where applicable, during chemistry selection and optimization activities.*

Rationale: *Failure to address these issues during the initial selection process is quite likely to lead to problems in one or more evaporator circuits. In cases where water from the LP evaporator drum is used for attenuation, steam purity may be affected (see Section 5.6.4).*

Potential HRSG Damage: *Unit-specific, varies with cycle design and chemistries in use; possible deposition and corrosion problems in evaporator circuits and superheater.*

In designs where feedwater is supplied directly to each evaporator circuit, and blowdown from drum evaporator circuits is directed to waste, the feedwater (see Section 5.7) and HRSG evaporator (see Section 5.8) selection processes are generally straightforward. Conversely, those designs that allow evaporator water from one circuit to be introduced to other circuits, either as feedwater or via cascade blowdown are more complicated and thus require more diligent efforts to select and optimize treatments [5-2]. Key issues that must be considered when selecting chemistries for these designs include the following.

- Will the treatments selected avoid single phase FAC in the LP evaporator?
- Can treatments effective in avoiding two-phase FAC be used in the LP evaporator?
- Can steam purity be maintained within limits when using the selected treatments?
- Do the selected treatments afford sufficient protection against evaporator tube corrosion damage in units that do not include condensate polishers and or tight condensers?

5.6.3 Deaeration

Action 5.6c *Select dissolved oxygen levels consistent with feedwater chemistry most suitable for monitoring and maintaining at low levels during all operating modes.*

Action 5.6d *Design how deaeration will be accomplished, both within the cycle and for treated makeup water.*

Rationale: *Deaeration is important to avoid the introduction of highly oxygenated water into HRSG tubes during startups and normal operation.*

Potential HRSG Damage: *Optimization of the feedwater treatment requires effective control of dissolved oxygen ingress, even when AVT(O) or OT will be used; failure to control the oxygen invariably leads to feedwater (pre-HRSG) component corrosion activity, deposition in*

evaporator circuits, increased risks of chemistry related HTF, and more frequent chemical cleanings. During idle periods, pitting corrosion is the most predominant result; oxygen pits also can serve as precursors to other corrosion-related HTFs.

Specific design decisions will be required if deaeration is to be included. Issues to be determined include:

- How is deaeration going to be accomplished?
- Will it be possible to deaerate water used to fill the system for startups?
- When during startup will deaeration become functional?
- Will auxiliary steam be used for the deaeration sequence on startup?

As with conventional cycles, deaeration can be accomplished in the condenser and/or in a separate deaerator. There are also LP evaporators that are “integral deaerators” [5-7, 5-8]. The steam circulation loop of the LP evaporator section is through the feedwater storage tank of the deaerating heater. It should be noted that this arrangement precludes the use of phosphate treatment since attemperator spray water would come from the integral storage tank. The interim chemistry guidelines suggest ways in which deaerated makeup water may be produced [5-2].

A once-through HRSG design installed in several locations in the US and Canada utilizes no deaerator and essentially operates on OT [5-6]. Any deaeration that does occur takes place in the air removal section of the condenser. Condensate dissolved oxygen levels in this cycle coincide with typical condenser specifications at 40 ppb [5-6].

5.6.4 Attemperation Water

Action 5.6e Assess probable impacts of attemperation on steam purity.

Rationale: To protect steam tubing and turbine from damage.

Potential HRSG Damage: Deposition and corrosion in superheaters and reheaters.

As is the case with conventional fossil units, superheated and reheated steam generated by HRSGs often requires attemperation to control temperature in a satisfactory manner. The water used for this purpose must approach or equal the quality of the steam required at the steam turbine inlet. Therefore, the contaminants entering the steam from the attemperation water, when mixed with the contaminants in the superheated and reheated steam, cannot exceed the limits established for the steam to the steam turbine inlet.

Certain combined cycle designs utilize LP evaporator/drum sections that are integral deaerators. With these designs, the attemperation water is furnished from the LP section. This precludes the use of solids based non-volatile treatments (phosphate or caustic) for the LP system since the phosphate or caustic would contaminate the superheated or reheated steam. This design necessitates the use of AVT or OT in the LP section to prevent contamination of steam to the steam turbine. Solids based treatments could be applied in higher pressure circuits, providing that no blowdown is directed to the LP section.

Design: Fluid Side

Should a situation exist where solids based treatment of the LP system appears necessary, say to mitigate flow-accelerated corrosion, consideration should be given to alternative attemperation water sources or methods. For example, it may be possible to employ LP feedwater, condensate, or treated makeup for spray attemperation. Noncontact attemperation by means of a heat exchanger (sweetwater condenser) would allow use of solids treated water for attemperation without contamination of the steam.

5.6.5 Feedwater Heaters/Preheaters.

Action 5.6f Consider the materials of any feedwater heater or preheater circuits as part of the feedwater treatment selection and optimization process.

Rationale: Differences in materials used in these components, when present in the cycle design, may influence how the treatment is selected and optimized.

Potential HRSG Damage: Possible deposit related damage (by mechanisms such as underdeposit corrosion and overheating) exacerbated by corrosion within the feedwater heater and/or preheater circuits.

Low pressure feedwater heaters are seldom included in combined-cycle power plants. One reason for this is that the allowable economizer inlet temperature can be low (natural gas operation). Also, if some feedwater preheating is required, pegging steam from the HRSG can be used. If a feedwater preheater is included in the cycle and oxygen levels are anticipated to be high, the preheater may be fabricated with a ferritic stainless steel (Type 430) [5-9]. Other materials mentioned as being used for preheaters include Types 304, 2205, or even carbon steel [5-7].

Since the heat cycle for combined cycles are all-ferrous in nature, except perhaps for the steam condenser, no compromise need be made in the matter of pH control, as required for mixed-metallurgy cycles. Also with proper water chemistry, such systems are amenable to oxygenated treatment as well as all-volatile treatment AVT (O) using no reducing agent. (See Reference 5-2 and Section 5.7 for further information.)

5.7 Design the Optimum Feedwater (or Pre-HRSG or Pre-Deaerator) Treatment

Action 5.7a Establish optimum feedwater (or pre-HRSG or pre-Deaerator) treatment based on decision roadmap (Figure 5-1).

Action 5.7b Ensure that, for all-ferrous systems, the feedwater must be on either all-volatile treatment, specifically AVT(O), or oxygenated treatment (OT).

Rationale: To minimize the generation and transport of iron oxides into the HRSG and turbine; to prevent corrosion of the pre-HRSG cycle components.

Potential HRSG Damage: HRSG tube failures; failure of piping and tubing within the feedwater system due to flow-accelerated corrosion; feedpump fouling; HRSG deposits that can act as centers for underdeposit corrosion mechanisms.

The design of the optimum feedwater treatment and its confirmation during the commissioning process are critical steps in avoiding HRSG pressure part damage. This section, along with the next (Section 5.8) on optimizing the HRSG treatment for each pressure circuit, is vital. Its position at this point in the chapter reflects the fact that a number of decisions will be required (Sections 5.3-5.6) prior to the design of the cycle chemistry methods; it does not however, reflect a decision of lesser importance.

HRSGs are typically designed with all-ferrous feedwater systems that usually involve a preheater, deaerator, and connecting pipe work. Thus, the pH constraints inherent with mixed-metallurgy systems are removed. It should be noted that the condenser may be tubed in a copper base alloy or titanium, but this does not significantly affect the selection and optimization process.

Briefly, there is really no choice for the optimum feedwater (or pre-HRSG or pre-deaerator) treatment. For all-ferrous systems, it must be either all-volatile treatment, specifically AVT(O), or oxygenated treatment (OT). This means that either only ammonia is added to the feedwater without any reducing agent, or that some small level (defined in the guidelines [5-2]) of oxygen is added. This will ensure that the lowest level of corrosion products are transported to the LP evaporator and are generated in the LP evaporator. It will also ensure that no single phase FAC can occur in the feedwater and evaporator circuits. It will not ensure that two phase FAC does not occur in the LP evaporator and LP drum. This will need to be optimized from a chemistry viewpoint during commissioning (see Chapter 10). Thus facilities need to be provided for the injection of ammonia and possibly oxygen.

In cycles with all-ferrous alloys, the feedwater treatments that could be used are shown in Table 5-2. Which of these feedwater treatments should be used and whether a reducing agent should be used at all can only be determined by field testing. The roadmap for optimizing the choice of a feedwater treatment is provided in Figure 5-1.

Table 5-2
Feedwater Treatment Choices [5-2]

Treatment	Conditions
Oxygenated	Condensate polishers
All-volatile with: • Ammonia • Organic amines [5-9 through 5-11]	• All situations • Must be evaluated, very little experience.

Design: Fluid Side

5.7.1 Objectives of Feedwater Treatment

The main objective of the feedwater treatment with all-ferrous metallurgy is to minimize generation and transport of iron oxides into the HRSG and turbine, and to prevent corrosion of the pre-HRSG cycle components, including the economizer or preheater, during operation and layup.

Additional objectives include:

- Avoidance of generation of corrosion and scale forming decomposition products
- Compliance with environmental regulations during operation, layup, and discharging and handling of chemicals

During normal operation, the iron concentration in the final feedwater (at the economizer or HRSG inlet) should be < 5 ppb and can easily be < 2 ppb. Lower concentrations are desirable and achievable. Combined cycle units with air cooled condensers, however, may find it difficult to achieve this limit.

5.7.2 Typical Feedwater Problems

The main problem is the generation of iron species containing corrosion products (iron hydroxide, iron oxide hydrates, and iron oxides), their transport around the cycle, and their deposition in specific cycle regions. The generation of corrosion products occurs mainly due to general corrosion and FAC of preheaters, deaerators, economizer inlet tubing and piping, and feedwater piping.

Consequences of this primary problem include:

- Failure (sometimes catastrophic and fatal) of piping and tubing within the feedwater system due to FAC
- Feedpump fouling
- HRSG deposits which can act as centers for underdeposit corrosion mechanisms
- HRSG tube failures
- Flow distribution orifice fouling
- Frequent chemical cleans

5.7.3 Decomposition of Amines and Reducing Agents

Amines other than ammonia will thermally decompose in the HRSG and the steam circuits, forming organic acids, carbon dioxide, and other decomposition products. This also happens to reducing agents other than hydrazine. Corrosion and FAC effects and removal of harmful decomposition products must be considered when selecting a feedwater treatment. Attention also needs to be given to the concentration of reducing agents and organics in the LP HRSG evaporator circuit. The decomposition products may represent a corrosion risk to the turbines

and may reduce the efficacy of cation conductivity measurements for monitoring steam purity. The harmful effects of some of the decomposition products may be reduced when condensate polishers are used, but generally the concern is for the turbine.

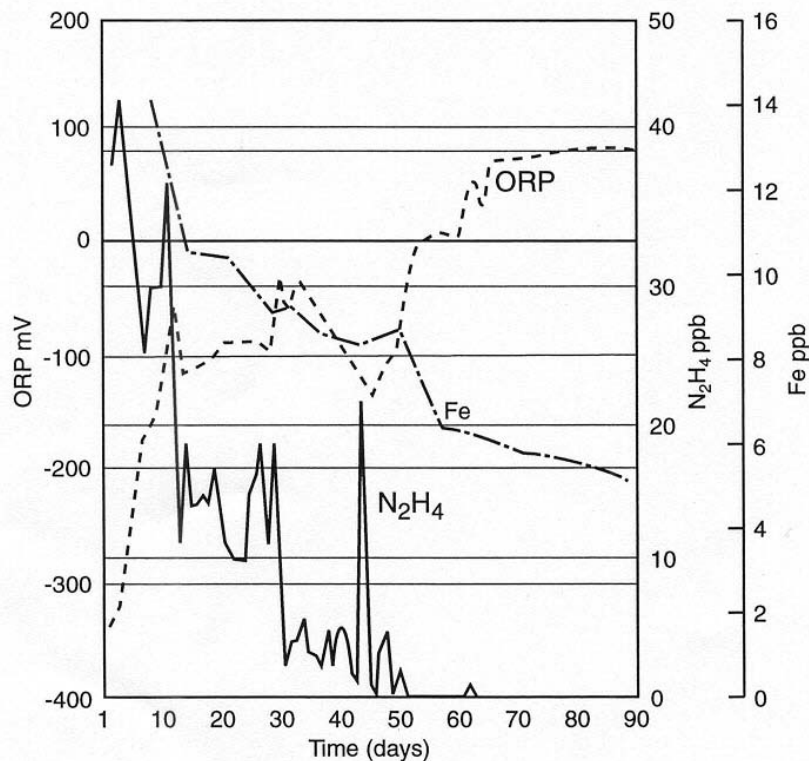
5.7.4 Feedwater Treatment Approaches

In the area of water chemistry, the objectives of optimization are achieved either by selection of a pH value in cycle streams that is high enough to minimize generation of corrosion products in the plant cycle ($\text{pH} > 9.5$) or by an OT. With both alternatives, controlling impurity ingress from condenser leaks and air in-leakage is essential, as well as very quickly reaching the normal guideline values during and after each startup.

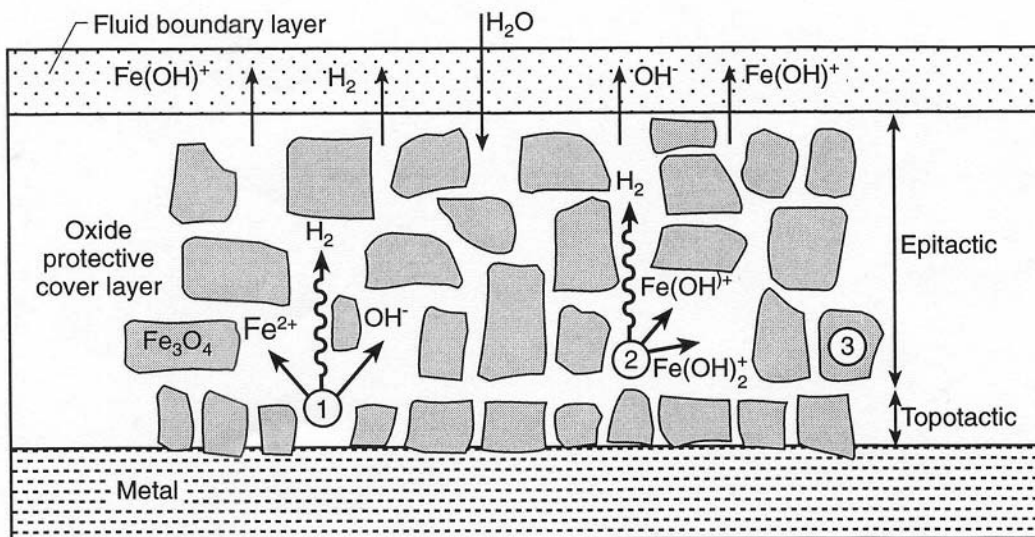
TOC and total halogenated organic matter (TOX) in the makeup water, or via condenser leaks from cooling water, can lead to an increase of cation conductivity and chloride in the feedwater, and a reduction of pH. This needs to be taken into account when selecting the method of feedwater conditioning (AVT or OT) and the optimum method of HRSG water treatment for units with drum cycles.

5.7.4.1 All-Volatile Treatment. The basis of AVT is an elevated pH in all plant cycle streams. The most common alkalizing agent used in AVT is ammonia. Originally, the ammonia dosing was always combined with the reducing agent. Investigations and experience have shown that reducing and even eliminating hydrazine (or other reducing agent) feed minimizes the corrosion product generation [5-12]. Figure 5-3 illustrates the results for an all-ferrous system operating with AVT (R).

Figure 5-4 illustrates the magnetite formation on all-ferrous feedwater materials operating with deoxygenated AVT.

**Figure 5-3**

Changes in Oxidizing Reducing Potential (ORP) and Feedwater Iron Levels (Fe) at the economizer inlet when Hydrazine (N_2H_4) is gradually reduced on a 600 MW drum unit with an all-ferrous feedwater system.

**Figure 5-4**

Schematic representation of oxide formed on iron-based feedwater surfaces during operation with AVT (R).

AVT with ammonia is often combined with the use of hydrazine or another reducing agent. In many cases, the application of a reducing agent is not required [5-12]. It has been shown that reducing or eliminating the dosing results in a decrease of feedwater total iron content and provides protection against FAC. The feedwater treatments using organic amines are often (but not always) combined with a reducing agent. Generally with AVT, an alternate amine and/or an organic based reducing agent are not desirable or needed in cycles with HRSGs. With these alternate treatments the feedwater chemistry must be optimized through an extensive monitoring program.

5.7.4.2 Oxygenated Treatment. While elevated pH is the basis of AVT, OT uses oxygenated high purity water to minimize corrosion and FAC in the pre-HRSG cycle. Oxygen, hydrogen peroxide, and air have historically been used as oxidants. Oxygen is the preferred choice.

For the application of OT in units with once-through and drum HRSGs, the one indispensable prerequisite is that the cation conductivity must be less than $0.15 \mu\text{S}/\text{cm}$ (at 25°C , 77°F) in the condensate, feedwater, and steam. An added prerequisite for drum units is that the cation conductivity in the HRSG boiler water (or downcomer) must be less than $1.5 \mu\text{S}/\text{cm}$ (at 25°C , 77°F), with care to avoid downcomer entrained oxygen.

The basis of the success of OT depends on the formation of a layer of ferric oxide hydrate (FeOOH) on the surface of the magnetite oxide layer and within the pores, which is much less soluble in feedwater than magnetite. This is illustrated in Figure 5-5.

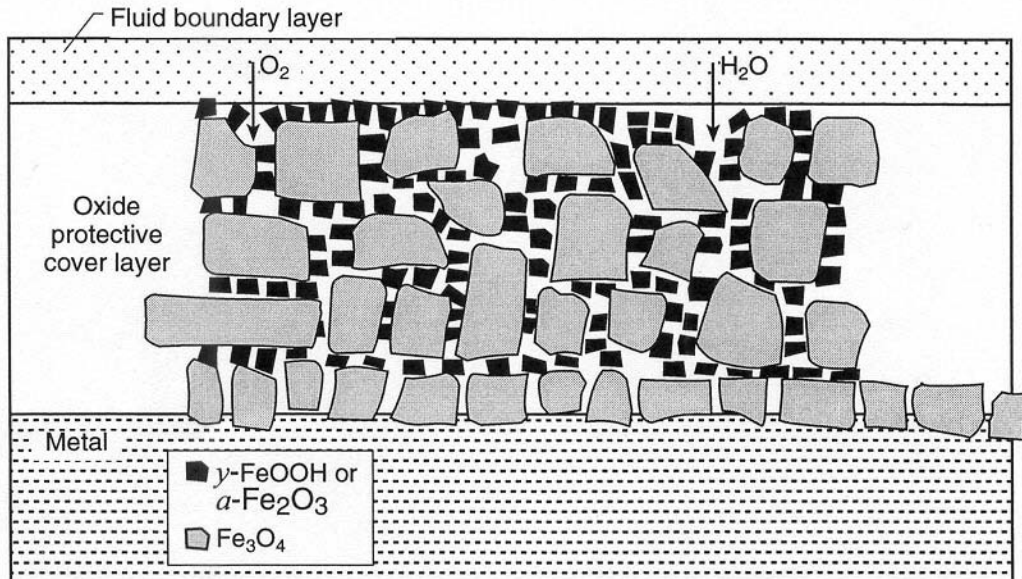


Figure 5-5
Schematic representation of oxide formed on iron-based feedwater surfaces during operation with OT.

5.7.5 Organic Feedwater Treatment Chemicals

Use of new organic feedwater treatment chemicals (alkalizing agents and/or reducing agents) needs to be thoroughly evaluated concerning their decomposition, monitoring, analytical interferences, and toxicity. As a rule, none of the organic feedwater treatment chemicals are desirable or needed in HRSG cycles with all-ferrous feedwater systems.

5.7.6 Startup Versus Normal Operation

Particularly during startup, an increased corrosion product transport occurs around the cycle. This is true mainly for feedwater systems operated on AVT. Major improvements can be achieved by proper layup of the unit or by operating with OT [5-2]. Improvements can also be achieved by operating without a reducing agent.

5.8 Design the Optimum HRSG Treatment for Each Pressure Circuit

Action 5.8 Determine suitable evaporator treatment strategy during the design phase to allow verification and refinement during the commissioning period (see Chapter 10).

Rationale: Most early HTF are related to improper HRSG cycle chemistry treatment.

Potential HRSG Damage: A variety chemistry-related HTF; of particular concern is flow-accelerated corrosion.

In the HRSG Cycle Chemistry Guidelines [5-2] there is a roadmap, shown in Figure 5-2, and associated descriptions of each step, which ultimately lead to the optimum choice of treatment for each pressure circuit. This roadmap is intended to simply overview the required activities, and those interested should refer to the details in the guidelines [5-2]. It should be understood that, in some cases, it may not be appropriate to utilize the same HRSG treatment in all evaporator circuits.

The guidelines [5-2] include sample points, action levels, and target values for the following chemical treatment philosophies:

- Phosphate Treatment Methodologies for drum type HRSGs
 - Phosphate Treatment (PT)
 - Equilibrium Phosphate Treatment (EPT)
- All-Volatile Treatment(AVT)
 - Drum Units
 - Once-Through Units
- Caustic Treatment (CT) for drum-type HRSGs
- Oxygenated Treatment (OT)

- Once-Through Units
- Drum Units

It will be immediately obvious that the first step requires some prognosis of the ability of the future unit to produce high purity feedwater (defined here as being better than 0.3 $\mu\text{S}/\text{cm}$ cation conductivity). Clearly, the inclusion of a condensate polisher in the design makes the answer to Step 1 obvious. The issue of a condensate polisher versus a “leak tight” condenser was discussed in Section 5.5.

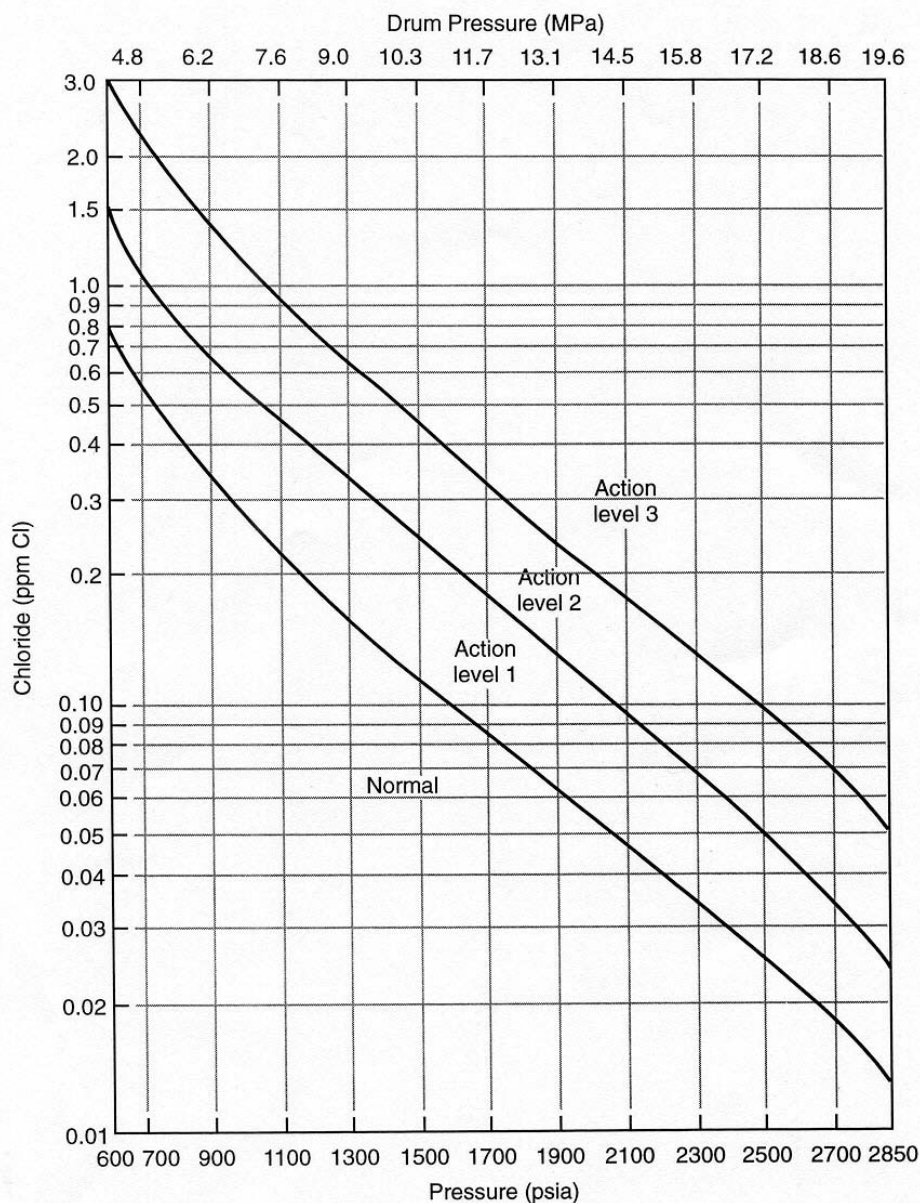
5.9 Setting Impurity Targets and Action Levels

Action 5.9 Establish customized limits for parameters such as sodium, silica, cation conductivity and organics based on EPRI Guidelines.

Rationale: *The EPRI Guidelines are based on research to define levels of contamination that should not lead to corrosion and deposition problems. Customization of the guidelines to individual combined cycle units provides maximum reliability and flexibility in dealing with contaminant ingress.*

Potential HRSG Damage: *A variety of corrosion and deposition problems, particularly in the evaporator sections of the HRSG and in the steam turbine.*

Normal target values for chemistry monitoring and control parameters need to be established based on the treatment approaches discussed previously [5-2]. It should be noted that a differentiation between reheat and non-reheat designs is made for target values for drum units on AVT, PT, and EPT, but not for once-through units on AVT and OT, or drum boilers on OT and CT. This differentiation is factored into control curves for HRSG boiler water, which may be used to ensure generation of high purity steam, based on consideration of both mechanical and vaporous carryover as a function of pressure. Figure 5-6 is an example of a control curve for chloride, which is applicable to HRSGs on EPT [5-2].

**Figure 5-6**

Equilibrium phosphate treatment: Boiler water chloride vs. operating pressure (HRSG/combined-cycle plants with reheat).

Action levels for control parameters at critical sample points need to be set. Recommended levels have been established [5-2]. These recommendations are based on current, state-of-the-art knowledge and will be revised based on a periodic review of experience. Four recommended action levels were established based on the following criteria:

- **Normal** – Values are consistent with longterm system reliability. A safety margin has been provided to avoid concentration of contaminants at surfaces.

- Action Level 1 – There is a potential for the accumulation of contaminants and corrosion. Return values to normal levels within 1 week.
- Action Level 2 – The accumulation of impurities and corrosion will occur. Return values to normal levels within 24 hours.
- Action Level 3 – Experience indicates that rapid corrosion could occur, which can be avoided by shutdown of the unit within 4 hours.
- Immediate Shutdown—HRSG Drum Units – There is clear evidence of rapid HRSG tube damage by low boiler water pH. Immediate shutdown of the unit is required to avoid such damage.

If the problem is not corrected within the time allotted to each action level, the next higher action level takes effect. In drum units having the capability of sliding pressure operation, one way to return from an action level condition is to reduce boiler pressure until the source of contamination ingress can be identified and corrective action taken.

The target values for Action Levels 1, 2, and 3 were established to allow and provide guidance during transient or abnormal operating conditions. The following criteria were used for most of the parameters:

- Action Level 1 Value: $2 \times [\text{Normal Target Value}]$
- Action Level 2 Value: $2 \times [\text{Action Level 1 Value}]$
- Action Level 3 Value: $> [\text{Action Level 2 Value}]$
- Immediate Shutdown: HRSG boiler water pH indicates a serious acidic contamination (Drum Units).

It should be noted that a factor of less than 2x is used for CT to allow a practical “normal” operational band (or limits) to be achieved within reasonable action level safety limits [5-2].

Operation at the lowest achievable impurity levels, with the shortest and least frequent excursions, is the most desirable mode of operation. The probability of corrosion damage and deposit formation grows significantly with increasing impurity concentration, and the damage is proportional to the exposure time. When corrosive impurities concentrate on metal surfaces, the breakdown of passivity (damage to the protective oxide layer) occurs within a few minutes to several hours.

During excursions, when the impurity concentration increases sharply, the accumulation of impurities in the cycle (turbine, HRSG, and SH deposits) occurs quickly, but the subsequent cleanup or return to good chemistry may take weeks. Therefore, yearly time accumulations should also be established as a guide.

Another useful approach to damage accumulation control is to set an annual goal for all key parameters of “(contaminant concentration) x (days).” Basically, this approach involves setting a limit on the absolute amount of contaminant transport to a component per year. Contaminant concentrations are then monitored for fixed lengths of time, multiplied by the respective sampling periods, and totaled over the year. The yearly concentration-days calculated in this

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way can then be compared with the set limit. This approach has been used to rate unit chemistry, compare performance of multiple units, and serve as an input for assessing the need for boiler chemical cleaning.

5.10 Ancillary Design Features to Ensure Overall Optimum Cycle Chemistry for the HRSG

Ancillary features of interest include shutdown and layup facilities, air in-leakage control capabilities, and facilities for chemical cleaning. These are addressed in the next three subsections.

5.10.1 Shutdown and Layup Facilities.

Action 5.10a Develop appropriate layup procedures (key aspects of shutdown procedures are described in Section 4).

Action 5.10b Design facilities needed to execute the proper unit shutdown and layup.

Rationale: The incursion of oxygen during unit shutdown where vacuum is broken can cause damage throughout the HRSG by increasing corrosion products and initiating corrosion/pitting damage.

Potential HRSG Damage: All of the cycle chemistry induced mechanisms including: deposits, underdeposit corrosion mechanisms, pitting, stress corrosion cracking and corrosion fatigue.

It is not uncommon for HRSGs to be shut down for periods of time extending from a few weeks to months due to dispatching demands in a given locality or resulting from seasonal adjustments. For cyclic operation where the HRSG may be shut down for periods long enough for vacuum to be broken, the likelihood of oxygen ingress is virtually guaranteed. It is very important to prevent this from happening. The HRSG Guidelines [5-2] include an extensive section on shutdown and layup requirements and guidance. A number of additional sources of information have been published relative to shutdown and layup and are available for review [5-13 through 5-20]. It cannot be emphasized enough how important it is to design in the facilities to ensure that proper conditions can be maintained.

Current layup practices vary widely, from the protection of all cycle components during longterm boiler layup, to providing no protection to any component. There should not, however, be any difference in the degree of corrosion protection provided during a short term or longterm layup. The most significant differences between the two are in the cost of layup chemicals, layup preparation, and maintenance.

Depending on preference and the duration of the outage, either a wet layup or dry storage method could be employed to prevent corrosion problems.

In general, with the exception for units on OT, wet layup requires filling of most of the system with an alkaline reducing solution and preventing air ingress by pressurization with an inert gas

(nitrogen). Restart of the unit is done after the unit is flushed with nitrogen gas and refilled with condensate.

Good experience has been reported for the second variant of wet layup of conventional drum boilers, utilizing a nitrogen blanket, while maintaining the boiler water at the same composition as during operation, without the need for the addition of a reducing agent [5-20]. To use this procedure on HRSG/combined cycles, the individual boiler design must be carefully considered when determining the number and location of nitrogen feed points: no HRSG boiler part at any time should be exposed to vacuum. However, it is clear that one feed point will not be sufficient.

For HRSG units in peaking service, it may be desirable to utilize auxiliary steam or steam from an operating HRSG to keep the idle unit in a hot standby condition. Where feasible, this approach effectively protects the idle unit, minimizes return to service time and avoids conditions, which can lead to HTFs by low cycle fatigue [5-2]. However, a steam supply is not always available for this purpose and the HRSG arrangement often does not readily and economically support maintenance of hot standby conditions.

Dry layup requires drainage while hot, and removal of all water followed by pressurization with a moisture free inert gas or by use of dehumidified air to maintain a low moisture environment. Dry layup is a viable approach if the relative humidity can be kept below 60%, as corrosion of carbon steel accelerates quickly at humidity levels higher than that. Of the options available to accomplish this, the preferred method is to drain the unit while still warm to dry all the steamside surfaces, chased with nitrogen under slight pressure to form a 'nitrogen blanket'. The unit is then bottled up for the duration of the time it is in layup. When returning the unit to service, the unit should be filled with condensate at the correct pH, not makeup containing excessive levels of dissolved oxygen.

In designing the proper layup procedure for a specific HRSG and its related equipment, the following points should be considered [5-21]:

- The compatibility between the chemistry required for layup and that used during operation.
- The possibility the HRSG may be required for operation on short notice.
- Facilities available for proper disposal of layup solutions.
- The possibility of freezing.
- A realistic assessment of the practicality of maintaining all the required conditions of a given procedure, i.e., complete dryness in dry layup or completely filled reducing conditions in wet layup (except for OT units).
- Local atmospheric conditions, e.g., salt air environment.
- The availability of sufficient high quality condensate, deaerated demineralized water, nitrogen, or dehumidified air during a unit outage

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5.10.2 Air In-Leakage Control Capabilities.

Action 5.10c *Ensure that the combined cycle unit design includes a means of monitoring condenser air removal rates in real time.*

Rationale: *Excessive air in-leakage rates introduce dissolved oxygen, carbon dioxide and dust and debris to the cycle. Control of air ingress is essential to effective chemistry control and optimal condenser performance.*

Potential HRSG Damage: *Increased rates of corrosion of carbon steel components and subsequent transport of iron oxides to the evaporators where they form deposits.*

Air in-leakage control is very important for both all-ferrous and mixed-metallurgy feedwater systems. For the former with AVT(O) good air in-leakage control allows optimum control of the oxidizing environment. For the latter it is a requisite to ensure that AVT(R) can be maintained. From a design viewpoint, reliable continuous monitors need to be included. (The operator should give additional consideration to the approach to be followed to identify sources of air ingress as they will inevitably develop over the operating life of the unit.)

5.10.3 Facilities for Chemical Cleaning.

Action 5.10d *Ensure that the unit design either includes permanent chemical cleaning piping and valves or allows satisfactory access for installation of temporary piping and valves when cleaning is required.*

Rationale: *Most HRSGs will require preoperational and/or operational cleaning, thereby necessitating a means to safely introduce cleaning solutions to the equipment and remove wastes from it with minimal risk of environmental impacts.*

Potential HRSG Damage: *Chemical cleaning is usually needed to condition the surfaces of new HRSGs prior to commissioning and commercial service. Operational cleaning should be performed as needed to eliminate and preferably to prevent those HRSG tube failure mechanisms requiring deposits to be present.*

Combined cycle unit design, and especially HRSG design must consider chemical cleaning, including preoperational and operational cleaning needs. Preoperational cleaning is included in Chapter 9. Operational cleaning will be required to address any underdeposit corrosion mechanisms or any deposition problems due to the use of polymer blends and/or polymer dispersants. An appropriate cleaning solvent should be selected for effective removal of the constituents anticipated to be of concern. Subsequently, the success of the cleaning typically rests with the ability to maintain the necessary process conditions, including solvent and component metal temperatures, solvent movement, and solvent chemistry (including acceptably low levels of solvent loss and solvent dilution). Design constraints can play a significant role on how cleaning will occur over the life of the unit.

The following design characteristics are a partial list of key considerations:

- In general, there is no effective and reliable means to set and maintain tube metal temperatures: the combustion turbine and duct burners (where provided) may not be available, for example, for preoperational cleaning. Further, the use of these components for chemical cleaning is not recommended since there is no effective means to control temperature and ensure an effective distribution of temperature over all surfaces to be cleaned.
- For solvents that require essentially continuous movement at specific temperatures to be effective, the design must provide accessible connections for suction and discharge of external circulation pumps. In most cases, the solvent will pass through an external heat exchanger before it is reintroduced to the HRSG.
- Filling and pressure pump connections, including valves, must be provided to the individual pressure systems for subsequent pressure tests. Chemical cleaning connections should be flanged with gaskets, bolts and blinds.
- Local provisions for drum water treatment, steam and water sampling, chelating agent or hot phosphate cleaning, hot and cold layup and nitrogen blanketing should be included.
- Components subject to damage during these conditions should be removable without cutting or welding.
- The ability to minimize heat losses from the HRSG during cleaning is an important consideration; this is particularly important for solvents, which require minimal movement.
- An appraisal of the circuitry of the HRSG must be made to assess the volumetric flow rates and solvent velocities that can be attained using pumps that can be fitted to the suction and discharge connection points; in some instances, this analysis may indicate that several or possibly all circuits can be cleaned simultaneously while in others it may be necessary to limit the number of circuits exposed to the solvent.
- A means of isolation of the HRSG (or those individual circuits intended to be part of the solvent flow path) from components that are not to be cleaned is required to avoid loss of solvent and possible damage to other components.
- An assessment of the adequacy of system drains and vents must be made prior to cleaning to ensure:
 - Solvents can be added to the system.
 - Solvents can be moved within the systems consistent with the requirements of the selected solvent.
 - Hydrogen gas generated during iron removal as well as any other gases, which may otherwise accumulate and interfere with solvent movement can be purged from the system.
- Drains should be sized so that the system may be completely evacuated in one hour, and no more than two hours. The design process should also eliminate, as possible, nondrainable locations. If such locations cannot be eliminated, they must be considered when selecting solvents, process conditions and procedures to be followed.

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- The design of vents should focus on the existence of locations that may be subject to air binding or accumulation of gases produced during cleaning. While it is best to eliminate such concerns during design, they can, if necessary, be addressed during development of the cleaning procedure.

5.11 Summarizing Specific Cycle Chemistry Design Considerations - Organized by Individual HFT Mechanisms

The EPRI HTF Manual [5-1] delineates the mechanism and root causes of all currently known HTF. The purpose of this section is to overview those chemical influenced HTF mechanisms and tie them to the actions recommended above, and thus summarize the various aspects of cycle chemistry design. Detailed discussion of each mechanism can be found in [5-1].

5.11.1 Corrosion Fatigue

Corrosion fatigue is currently the leading cause of HTF [5-22]. These failures are initiated from the internal waterside surfaces of evaporator and economizer sections. Failures are typically located at any type of tube attachment or at welded attachments to headers, where expansion (mechanical or thermal) is restricted. Multiple arrays of cracks appear on the inside tube surface in an orientation which is perpendicular to the major strain. Corrosion fatigue is a discontinuous mechanism, which means that the very broad, oxide filled cracks, only propagate when there is concurrency of the strain and out-of-specification chemistry. The primary cycle chemistry influence is reduced pH.

The chemistry factors that need to be considered during the design phase include:

- Ensuring that the HRSG chemistry selected will not allow or cause pH transients (particularly reductions from normal operating levels). Here it will be noted that only two forms of phosphate treatment (EPT and PT) are included on the roadmap of Figure 5-2. This is to ensure that acidic phosphates are not added to the unit. Thus the design must indicate that if non-volatile phosphate treatments are to be used, that only trisodium phosphate should be specified. If blended phosphate mixtures will be used, they should not include di- or monosodium phosphate, polymers, or dispersants.
- Adequate HRSG instrumentation should be included to ensure pH is monitored.
- Adequate facilities should be included to ensure the HRSG can be shutdown or laid up under a protective nitrogen blanket or other media. This is to ensure that pits are not initiated during unprotected shutdowns, which can be initiating centers for corrosion fatigue.

5.11.2 Flow-Accelerated Corrosion

Flow-accelerated corrosion can and has occurred in single and two phase variants. The mechanisms, which occur essentially in the evaporator circuits and the LP drum, are both very well understood. Single phase FAC is controlled by the dissolution of magnetite from tube surfaces and predominates when the fluid has a reducing potential (ORP is generally less than 0 mV). Thus, no facility should be included during the design phase to add a reducing agent (such

as hydrazine) to the feedwater. Two phase FAC is much more difficult to control or eliminate during the design phase. It can only be identified once the possibility for single phase FAC has been removed and monitoring is conducted during the commissioning phase (Chapter 10). However, if this monitoring does identify the possibility of two phase FAC then the addition of a solid alkali will be needed to the LP circuit. Thus the design should include an injection port.

5.11.3 Underdeposit Corrosion

Underdeposit corrosion can and has occurred in three variants: hydrogen damage, acid phosphate corrosion, and caustic gouging. Each is very well understood. While each requires a different concentrating mechanism beneath a heavy deposit, the overall mechanisms are distinctly different. The design factors to be considered from a cycle chemistry viewpoint include:

- Hydrogen damage.
 - I. Ensure minimum feedwater corrosion products enter the HRSG by selecting the optimum feedwater treatment.
 - II. If non-volatile HRSG treatments are to be used, then ensure that polymers, blends and dispersants are not specified
 - III. Ensure sufficient instrumentation is available so that contaminant excursions (condenser leaks) can be identified and dealt with
 - IV. Ensure facilities are provided for chemical cleaning of evaporator circuits and that the drains are designed properly to allow cleaning waste to be removed.
- Acid Phosphate Corrosion
 - Items I, II and IV under hydrogen damage are applicable.
 - V. Ensure that HRSG treatment choice does not allow any phosphate other than trisodium phosphate to be added.
- Caustic Gouging
 - Items I, II and IV under hydrogen damage are applicable.
 - VI. Ensure optimum levels of caustic are added and maintained at less than 2 ppm
 - VII. During commissioning, need to ensure that Steps 21 and 22 in Roadmap (Figure 5-2) are conducted.

5.11.4 Pitting

Pitting is an insidious HTF mechanism in that it can occur in many of the tube circuits. However, in all cases pits are initiated and grow during periods when that circuit remains filled with oxygen saturated water or in locations where such water is allowed to pool. Thus the main design theme must be to ensure that facilities are added to (i) drain the circuit as efficiently as possible, and (ii) provide protection during the shutdown period in terms of nitrogen blanketing or other suitable media such as dehumidified warm air.

5.11.5 Waterside Deposits and Other Deposit-Influenced HTF Mechanisms

Waterside deposition is not an independent HTF mechanism. However, internal deposits are needed before underdeposit HTF mechanisms (See Section 5.11.3) become active. Also, deposits may influence the rate of corrosion and the extent of damage. HTF mechanisms which involve waterside or steamside deposits include the following:

- Hydrogen Damage (See Section 5.11.3)
- Acid Phosphate Corrosion (See Section 5.11.3)
- Caustic Corrosion (See Section 5.11.3)
- Long-Term Overheating
- Short-Term Overheating
- High Temperature Fireside Corrosion (Gas-side Corrosion and Pitting)

Still other mechanisms initiate by breakdown of the normally protective oxide layer on tube internal surfaces. In the case of waterside corrosion, deposits are a precursor to damage in that they serve to concentrate boiler water contaminants or treatment chemicals to corrosive levels. Internal deposits also impede heat transfer, thereby increasing the in-service temperature of the tube metal. As a result of increased temperature, the microstructure of the tube metal may be affected, leading to long-term overheating damage and failures. Accumulation of loose deposit materials may cause restriction of flow or stagnant conditions in water or steam touched tubes, leading to short-term overheating failures. At surfaces where fireside corrosion is active, increased metal surface temperatures caused by internal deposits will increase the rate of external corrosion and shorten the time to failure. In combined cycle units operated with fuels containing sulfur compounds, gas-side corrosion and pitting may be experienced. (No damage has been observed in units that utilize natural gas.) Other undesirable effects of internal deposits in HRSG tubing include thermal efficiency losses and changes in evaporator circulation; generally however, these secondary effects are comparatively minor and will not become evident before either HTFs are experienced or action is taken to remove the internal deposit material.

5.11.6 Stress Corrosion Cracking

Stress corrosion cracking (SCC) is a form of environmentally assisted cracking. As with corrosion fatigue (CF), the damage is within the spectrum of failures that develop due to fatigue (with no environment effect) and general corrosion (with no stress impact). Research investigations of SCC and CF have identified characteristics specific to each mechanism [5-1]. SCC may be generally defined as the initiation and growth of cracks in susceptible material simultaneously exposed to stress and a detrimental chemistry environment. The stress levels needed to develop SCC are significantly lower than those associated with overload failures.

5.12 References

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6

DESIGN: GAS SIDE

6.1 Overview of this Chapter

This section includes fuel characteristics and firing systems (Section 6.2), gas side flows and temperatures (Section 6.3), gas side condensate management (Section 6.4), and emission controls (Section 6.5).

6.2 Fuel Characteristics and Firing Systems

6.2.1 Introduction

The purpose of this section is to highlight fuel characteristics and the supplementary firing system factors that pose a potential risk to the integrity and longterm reliability of pressure parts, especially the tubes making up the varied sections of today's complicated, multi-pressure HRSG designs.

Currently, the majority of HRSGs installed internationally use flue gas generated from the combustion of natural gas, either in an unfired or fired mode. The use of light or distillate oil is also used, but usually only as an emergency or supplementary fuel. Depending on the CT rating, its operating temperature varies, with the smaller units operating at lower temperatures. The lower the temperature level, the more forgiving the CT design to accommodate lower rank fuels. These fuels, such as crude oil, waste stream gases and coal gas generally contain sufficient impurities so as to potentially affect HRSG operation and create scenarios that can impact longterm reliability if the design/operation is not ideally suited for the application. The most problematic constituent is the fuel sulfur content.

The ideal economic generation model for a given installation varies. Many times, supplementary firing is used in the HRSG to increase the Rankine cycle (steam turbine) generation contribution so as to increase total plant electric generation output. This is accomplished at the expense of optimum cycle efficiency or heat rate. When additional generation is required, the required steam generation is accomplished with burners installed at a location near the inlet of the HRSG or directly after one or more of the high temperature superheater or reheater heat exchanger sections. It is customary for the burners to utilize the available oxygen in the CT exhaust as the oxidant. Utilizing this approach, it is not uncommon to generate up to twice as much steam as the unfired case while maintaining the burner downstream flue gas temperatures within a range of 815 – 871°C (1,500 - 1,600°F), the normal maximum flue gas temperature in the non-watercooled HRSG inlet ducting section.

Design: Gas Side

6.2.2 Fuel Characteristics

Action 6.2a *Evaluate potential fuels for the effects on HRSG pressure parts.*

Action 6.2b *Determine the likelihood for firing fuels containing more than minimum levels of sulfur.*

Rationale: *Firing fuels that contain sulfur will affect the morphology, formation rate, thickness and strength of the protective oxide layer on the outside of HRSG tubes. Potential design features to deal with sulfur containing fuels will be needed if it is anticipated that the unit will fire, or normally co-fire with sulfur containing oil.*

Potential HRSG Damage: *There is a potential for HRSG tube damage by gas side corrosion, acid dewpoint corrosion or stress corrosion cracking. Oil firing can also cause fouling of finned tubes and loss of heat transfer capability.*

HRSGs receive exhaust gas from firing by a variety of fuels. The design process should reflect whether, for operating flexibility, there is to be firing of multiple fuels. Unlike conventional boilers, which can be designed for firing specific fuels from a myriad of sources, the principal energy source for the operation of a HRSG is the elevated temperature exhaust stream from a CT. The flue gas is the product of combustion of fuels whose properties are dictated by the design limitations of the CT components, which are intolerant of the operating conditions and constituents normally found in conventional boiler fuels. Therefore, factors such as high heat flux, fly ash erosion and high temperature ash corrosion are usually non-issues in the design of HRSGs and the boiler design standards applied to HRSGs are considered comparatively benign in terms of fouling criteria and pressure part material selection.

The most abundant, economical and environmentally friendly fuel for firing CTs is natural gas with distillate oil as a backup or supplementary source. Natural gas provides a relatively benign environment in both the hot end and cold end of the HRSG. Typical fuel analyses for these are provided in Table 6-1 [6-1].

Table 6-1
Natural Gas Analyses from Domestic U.S. Regions [6-1]

Sample No.	1	2	3	4	5
Source:	Pa.	S.C.	Ohio	La.	Ok.
Analyses:					
Constituents, % by volume					
H ₂ , Hydrogen	--	--	1.82	--	--
CH ₄ , Methane	83.40	84.0	93.33	90.00	84.10
C ₂ H ₄ , Ethylene	--	0.25	--	--	--
C ₂ H ₆ , Ethane	15.80	14.80	--	5.00	6.70
CO, Carbon monoxide	--	--	0.45	--	--
CO ₂ , Carbon dioxide	--	0.70	0.22	--	0.80
N ₂ , Nitrogen	0.80	0.50	3.40	5.00	8.40
O ₂ , Oxygen	--	--	0.35	--	--
H ₂ S, Hydrogen sulfide	--	--	0.18	--	--
Ultimate, % by weight					
S, Sulfur	--	--	0.18	--	--
H ₂ , Hydrogen	23.53	23.30	23.20	22.68	20.85
C, Carbon	7.25	74.72	69.12	69.26	64.84
N ₂ , Nitrogen	1.22	0.76	5.76	8.06	12.90
O ₂ , Oxygen	--	1.22	1.58	--	1.41
Specific Gravity					
(related to air)	0.636	0.636	0.567	0.600	0.630
HHV					
Btu/ft ³ at 60F and 30 in. Hg (KJ/m ³ at 16C and 102 kPa)	1,129 (42,065)	1,116 (41,581)	964 (35,918)	1,022 (38,079)	974 (36,290)
Btu/lb(kJ/kg) of fuel	23,170 (53,893)	22,904 (53,275)	22,077 (51,351)	21,824 (50,763)	20,160 (46,892)

The advantage of this fuel for use in HRSGs either as a waste heat and supplementary energy source is that it contains little or no sulfur, or other constituents that prove problematical operationally or damaging to components resulting in corrosion or erosion as described in [6-2].

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Another fuel that is in widespread use, especially where natural gas is not readily available or where natural gas quantities are interruptible, is light oil. This petroleum product is also known as distillate and it normally fits within the definition of No.1 or 2 oils as shown in Table 6-2 [6-3].

Table 6-2
Fuel Oil Analyses [6-3]

Grade of Fuel Oil	No. 1	No. 2	No. 4	No. 5	No. 6
% by weight:					
Sulfur	0.01 to 0.5	0.05 to 1.0	0.2 to 2.0	0.5 to 3.0	0.7 to 3.5
Hydrogen	13.3 to 14.1	11.8 to 13.9	(10.6 to 13.0)*	(10.5 to 12.0)*	(9.5 to 12.0)*
Carbon	85.9 to 86.7	86.1 to 88.2	(86.5 to 89.2)*	(86.5 to 89.2)*	(86.5 to 90.2)*
Nitrogen	Nil to 0.1	Nil to 0.1	--	--	--
Oxygen	--	--	--	--	--
Ash	--	--	0 to 0.1	0 to 0.1	0.01 to 0.5
Gravity:					
Deg API	40 to 44	28 to 40	15 to 30	14 to 22	7 to 22
Specific	0.825 to 0.806	0.887 to 0.825	0.966 to 0.876	0.972 to 0.922	1.022 to 0.922
Lb/gal	6.87 to 6.71	7.39 to 6.87	8.04 to 7.30	8.10 to 7.68	8.51 to 7.68
Pour point, F	0 to -50	0 to -4	-10 to +50	-10 to +80	+15 to +85
Viscosity:					
Centistokes at 100°F	1.4 to 2.2	1.9 to 3.0	10.5 to 65	65 to 200	260 to 750
SUS at 100°F	--	32 to 38	60 to 300	--	--
SSF at 122°F	--	--	--	20 to 40	45 to 300
Water and sediment, % by vol	--	0 to 0.1	tr to 1.0	0.05 to 1.0	0.05 to 2.0
Heating value, Btu/lb gross (calculated)	19,670 to 19,860	19,170 to 19,750	18,280 to 19,400	18,100 to 19,020	17,410 to 18,990
*Estimated					
Note: kJ/kg = Btu/lb x 2.326, kg/m³ = lb/gal x 119.8					

Currently, approximately 75 percent of new combined cycle plants have the means to accommodate supplementary firing [6-4]. There are no hard and fast rules for using the same fuels in both the CT and the supplementary firing, although there are logistic and economic advantages to using like fuels for both the CT and the HRSG burner unless suitable opportunity fuels are available for incineration or cost saving purposes. The important criterion is that the fuels must be completely compatible with the HRSG design features to prevent fouling and corrosion to preserve the thermal performance and reliability.

For use of any grade of oil or naphtha (a term applied to many petroleum, coal tar, and natural gas liquid byproducts, usually to a narrow boiling range fraction somewhere between kerosene and gasoline [6-5]) on a continuous basis, the HRSG must have provisions for cleaning heating surfaces on a periodic basis to preserve performance and prevent an irreversible fouling condition that would eventually result in problems with poor distribution, circulation, steaming in economizers, overheating and stress conditions leading to tube failure mechanisms outlined in [6-2]. This is usually accomplished by applying:

- In-line tubing configurations.
- Tube finning density not exceeding 5 fins per inch (approximately 2 fins per cm).
- Use of solid fins as opposed to segmented fins, which are less prone to fouling; see Figure 6-1 [6-6].
- Use of thicker fins for corrosion protection and mechanical strength to withstand the forces incurred during sootblowing.
- Control of the maximum depth of tube banks to 8 tubes.
- Installing sootblowers using air or steam for cleaning medium.
- Periodic cleaning of the HRSG utilizing either treated water to neutralize the acidic waterwash products or CO₂ in the form of dry ice pellets.

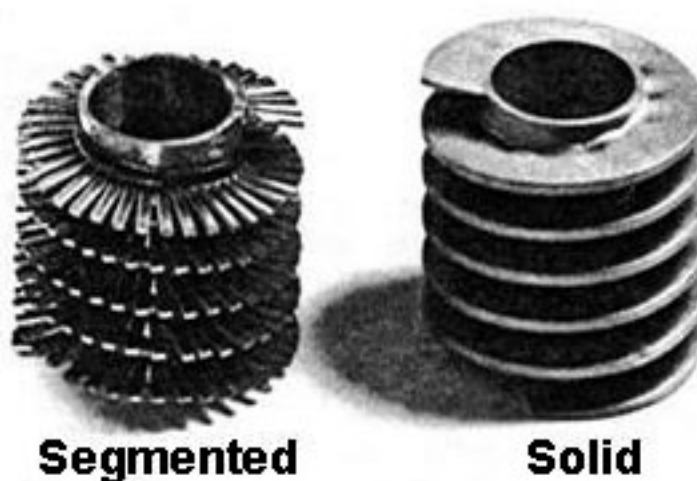


Figure 6-1
Finned tube types [6-6].

Firing these fuels on an intermittent basis in a unit designed for using natural gas, depending on the duration and frequency, can usually be done for a period not exceeding 200 hrs/yr without applying design or operating features normally used for a continuous use of that fuel.

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6.2.3 Firing Equipment

Development for CT application has resulted in burner technology improvements by nearly all manufacturers. The driving force has been and continues to be NO_x and CO emission reduction. The single most important development has been the pre-mix burner, which replaced the diffusion flame burner for natural gas and distillate oil. Also known as ‘dry low- NO_x ’ this burner can achieve NO_x emission levels as low as 9 ppm vdc (volume dry corrected) on large industrial frame machines firing natural gas and 50 ppmvdc on oil. A typical dual fuel burner is depicted in Figure 6-2 [6-7].

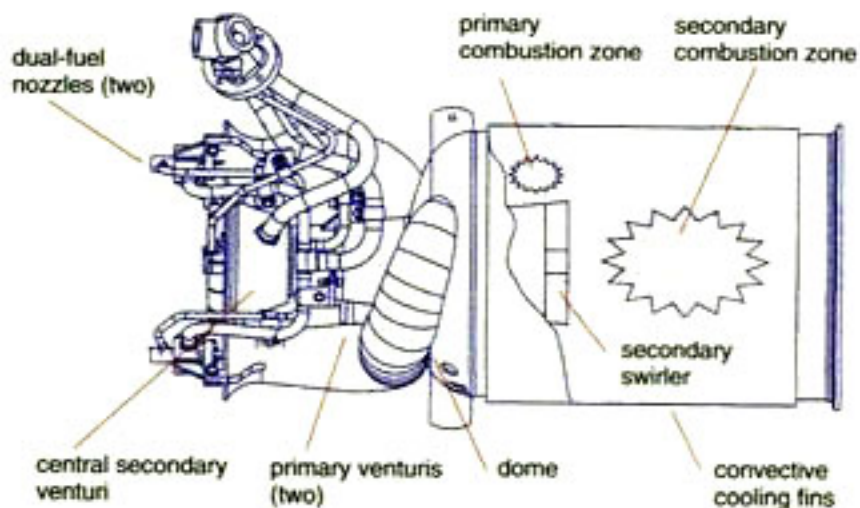


Figure 6-2
Dry low- NO_x – dual fuel premix burner [6-7].

For HRSGs requiring additional steam generation, the installation of a rack type diffusion duct burner is the conventional approach to supplemental firing. Although there is at least one supplier of premix type duct burners, the majority of suppliers provide ‘batwing’ diffusion type designs for use with conventional fuels, Figure 6-3. These burners are located either in the CT outlet/HRSG inlet ducting or within the HRSG structure downstream of one or more of the high temperature heat exchangers. The choice of locations is determined by the HRSG designer to meet specific heat balance constraints and material selections. Using the available oxygen in the CT exhaust stream (over 11 percent), these burners can raise the flue gas temperature by up to approximately 280°C (500°F) to a maximum temperature of $840 - 870^\circ\text{C}$ ($\sim 1550 - 1600^\circ\text{F}$) for protecting duct liners against overheating and still meet stringent environmental restrictions on NO_x , CO and VOC emission rates. Duct burners affect the heat exchanger size, and thus tube and finning design and material selection.

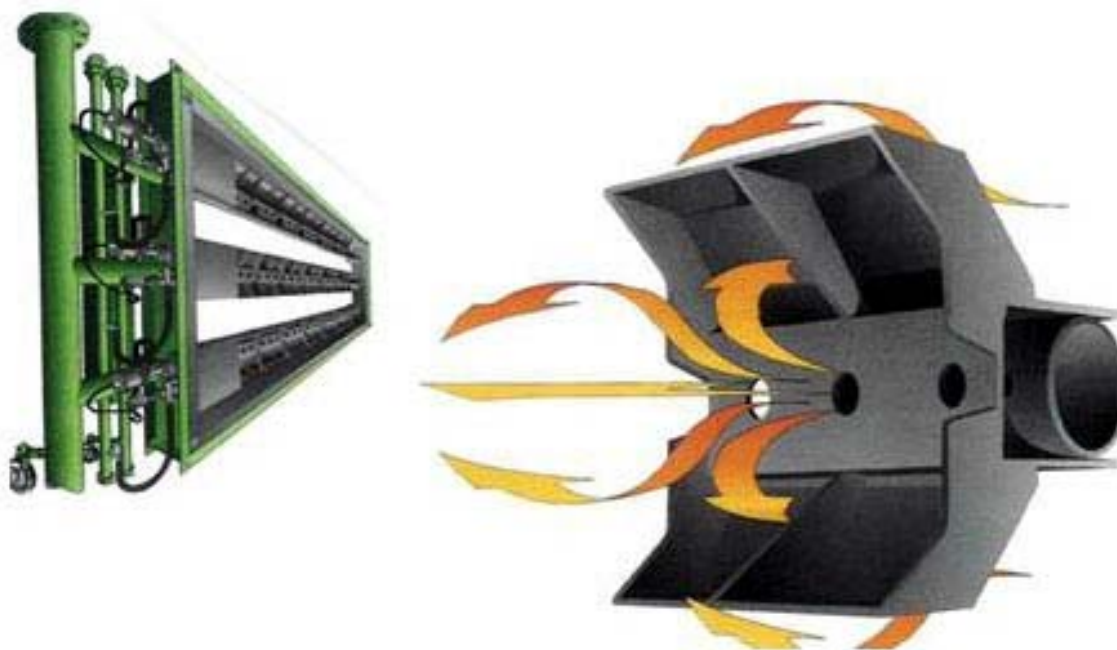


Figure 6-3
Typical duct burner (courtesy Coen Company).

6.2.4 Supplemental Firing

Action 6.2c During design of the supplemental firing system and export/extraction steam flows, include measures to avoid locally high temperatures in the HRSG.

Rationale: Temperatures in excess of nominal expected design can be a major contributor to a number of HRSG tube failure mechanisms.

Potential HRSG Damage: Short term overheating, increased evaporator tube deposition, increased potential for underdeposit corrosion mechanisms, and increased flow-accelerated corrosion due to increased flows.

Supplemental firing and export/extraction steam flows will have a major impact on HRSG design specification. This feature allows for generating more steam than is otherwise available from the energy in the CT exhaust stream. Improved operating flexibility will result from specifying a supplemental firing system capable of wide turndown and capable of handling wide exhaust gas flow variations.

Supplementary firing is used either continuously or intermittently to meet steam demand. When used, supplementary firing raises the combined cycle heat rate in proportion to the amount of firing. Supplementary firing affects the HRSG thermal performance significantly, as illustrated

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in Figure 6-4 [6-8]. The major changes in performance include the steam flow, which can be over twice the unfired rate, the pinch and approach temperatures tend to rise when unit is fired, the stack temperature is lowered due to the rise in water flow through the economizer, and the effect of a higher LMTD (log mean temperature difference) and increased heat transfer.

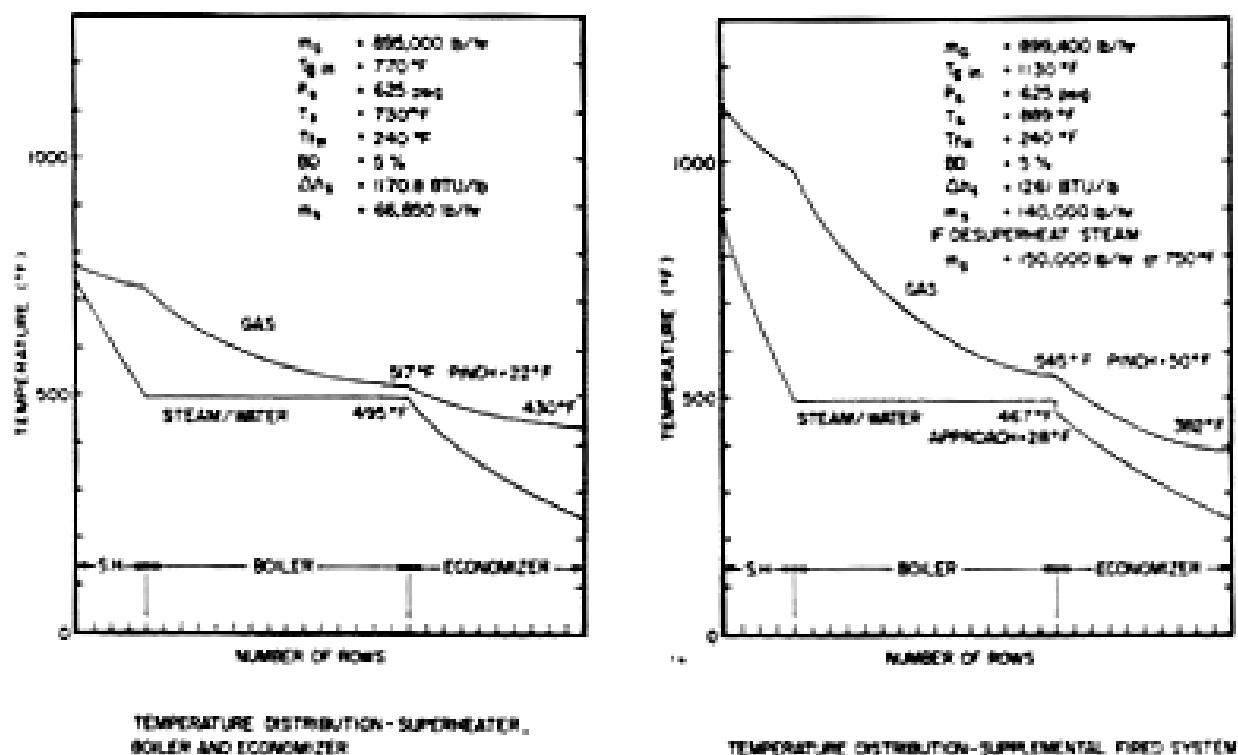


Figure 6-4
HRSG temperature profiles [6-8].

The maximum amount of supplementary firing, and thus the increase in steaming rate attainable, is based on two parameters:

- The available oxygen content in the incoming flue gas stream. The practical lower O_2 limit in the flue gas stream leaving the burner is between 9 – 10 %vol. Attempting to operate below that point may lead to excessive CO content.
- The maximum flue gas temperature leaving the burner is $843 - 871^\circ\text{C}$ ($1550 - 1600^\circ\text{F}$), to protect the HRSG inlet duct liner from damage due to overheating. Higher temperature levels are technically achievable to greater than 1093°C (2000°F). However, at these elevated temperatures, it is customary to consider water cooled enclosures as a substitute for lined ducts to prevent overheating damage to liners and insulation.

Because of elevated temperature levels, supplementary firing exacerbates the importance of maintaining adequate flue gas flow and temperature variation to prevent HRSG damage. As with all boiler types establishing the design margins on pressure parts based on these parameters is an inexact science.

Duct burner suppliers continue to attempt to quantify temperature and flow stratification through testing and modeling techniques. One ‘rule of thumb’ used to estimate the peak-to-peak temperature gradient entering the burner downstream HRSG section is $\pm 50\%$ of the burner temperature rise in the burner. The reasons for the high temperature and flow variation include:

- The CT type and size.
- The HRSG type.
- The aspect ratio and expansion characteristics of the inlet duct. Tall slender configurations tend to have high flow through the lower section, low flow in the middle section as the flow tends to ride up the front of the section and mid-flow in the upper heat exchanger region. Rectangular sections tend to expand horizontally.
- The operating point, maximum rating and fuel distribution within the respective burner branches.
- The absorbing/emitting effects of CO_2 and H_2O in the flue gas have proven to be significant especially in computing temperature variation downstream of the burner location in the near burner region.

6.3 Flows and Temperatures

Action 6.3a Specify OEM reports to identify conditions, especially on units having supplementary firing, that could result in pressure part damage or deterioration caused by excessive flows (see Section 4.5 for effects of excessive temperatures).

Action 6.3b Techniques to measure the flue gas distribution should be specified, along with their estimated accuracy.

Action 6.3c A three dimensional physical flow model should be constructed to help analyze expected flows, along with numerical simulation, such as by computational fluid dynamics. This will help determine the optimum arrangement of equipment, and the shape and location of gas distribution devices required.

Action 6.3d Instrumentation for measuring flow characteristics should be included during the design process and used during commissioning to confirm expected values.

Rationale: Excessive flue gas temperature and flow variances have significant potential impact on HRSG pressure parts.

Potential HRSG Damage: HTF mechanisms including short term and longterm overheating, underdeposit corrosion mechanisms, economizer steaming (leading to thermal fatigue), and departure from nucleate boiling leading to excessive deposition.

CT turbine power output has increased substantially. Commercial G class machines generate well over 250MW. The CT exhaust conditions under these conditions are approximately 2.0 million kg/h (4.5 million lb/h) of flow at 593°F (1100°F). Directed to the HRSG, this quantity of

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flow must be managed correctly to ensure correct HRSG performance, operation and reliability are attained.

With HRSGs, the flow and temperature profiles entering the heat exchangers, and/or downstream of the duct burner, are a function of the CT installed, the load, the off design cases, the HRSG type, the duct design features and the quantity of supplementary firing being done. It follows that quantifying exactly the conditions accommodating all the possible combinations is not likely. As a result, the HRSG and the burner OEMs estimate the “worst case” conditions by CFD modeling to form a design basis.

The CT OEMs tend to provide minimum parameter monitoring at the exhaust. For a GE Frame 7F CT, gas temperature is measured at 27 points on the outlet nozzle circumference [6-20], and no flow measurements are recorded. Therefore, the limited available information provides the HRSG OEM with limited data to form a design basis. Therefore, reliance on modeling and parametric post-commissioning data, when retrieved, is used. Presently, this data is not widely collected or published for horizontal and vertical HRSG applications.

The large machines produce an extremely turbulent flue gas stream entering the transition duct to the HRSG. See Figure 6-5 for a typical exhaust velocity profile.

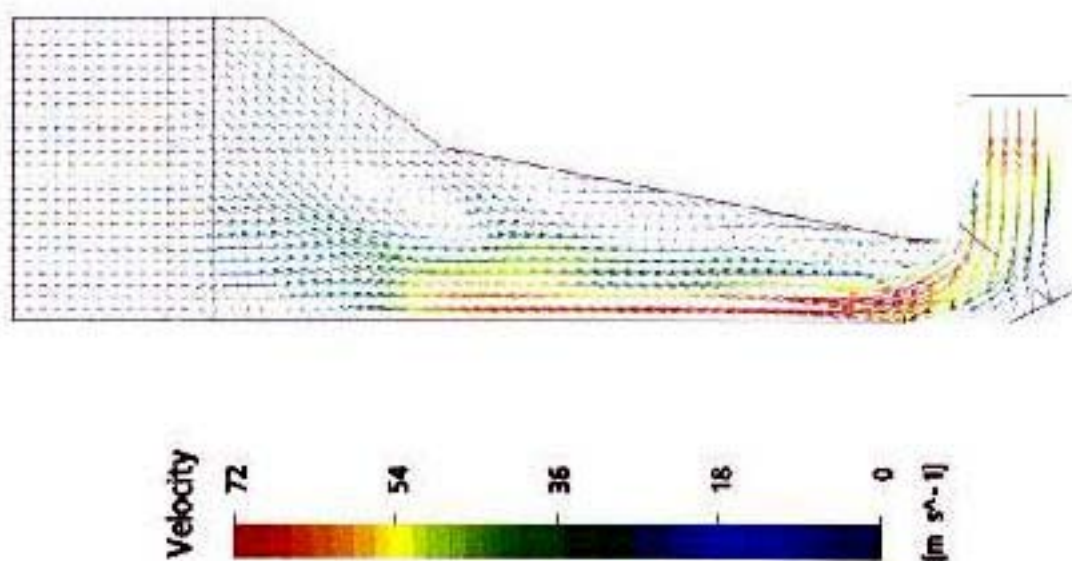


Figure 6-5
CT exhaust velocity profile.

With SCRs, which are normally located in the HRSG regions operating between 315 and 427°C (600 to 800°F) the uniformity of the flow field is crucial to ensure emission level limits are met without excessive ammonia slip. The gradation of flow also has a significant impact on the HRSG heat exchangers. With a flow stratification, the external heat transfer coefficient on the

tubing varies as the 0.61 power of gas flow [6-9]; a relatively small change in flow over finned tubing can dramatically alter the finned tube temperature profiles and thus change the performance of the unit. Further, this variation alters the tube expansion characteristics. Since all the tubes are rigidly attached to a given inlet and outlet header, a temperature difference in some of these tubes translates into a thermal expansion difference. The more stratified the flow the greater the difference in the amount of tube expansion and the greater the differential stress levels.

With the face area of a HRSG tube field on a unit this size usually close to 18.3 m (60 ft) high and 7.6 m (25 ft) wide and limited footprint length available between the CT and the HRSG, the transition angle can sometimes exceed 45°. With this expanding flow field, maintaining uniform velocity to within $\pm 10\%$ of the average poses a challenge. Normally, distribution plates, turning vanes or straightening devices are installed to attain this level of performance. See Figure 6-6 for a typical configuration. These devices are normally developed through the use of either a scaled physical model or a computational fluid dynamics (CFD) model.

HRSG temperature profiles vary to three major parameters: (i) the number of HRSG pressure levels, (ii) the pinch and approach temperature differential designed in and (iii) the level of supplementary firing that is done.



Figure 6-6
Flow straightening devices installed in HRSG.

6.3.1 Influences on Gas Flow Velocities and the Effects on Pressure Parts

The main driver in limiting flue gas velocity in HRSG systems is the impact it has on the HRSG gas side pressure drop. Since the pressure drop varies as the square of velocity, a doubling of the

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average velocity through the unit will quadruple the pressure drop and increase the backpressure on the CT thus lowering its power output. On the plus side, higher flue gas velocity results in a higher convective heat transfer coefficient, and thus the need for as much heating surface to perform equivalent duty.

Raising the flue gas velocity in the respective heat exchange sections will have the following impacts:

- It raises the fin tip temperature.
- It raises the heat flux into the working fluid.
- It raises the potential for vibration to occur.
- Because it raises the pressure drop, there is a flow equalization effect into the respective section.

The maximum average exhaust gas velocity in the HRSG directly upstream of the lead HRSG section will typically not exceed 22.86 m/s (75 feet/sec). As the flue gas travels through the HRSG, its velocity will drop as the temperature is reduced.

As part of the specification and HRSG design processes it is important that flue gas temperature and flow variances and their potential impact on pressure part selection be considered. Excessive variation in these parameters can lead to: (i) short term overheating, (ii) longterm overheating, (iii) departure from nucleate boiling (and short term overheating in HP evaporator section), (iv) underdeposit corrosion in all evaporator sections, (v) economizer steaming, and (vi) overstress and fatigue of selected tubing.

Techniques to measure the flue gas distribution should be specified, along with their estimated accuracy. To assess the existence of potential problems with temperature and flow distribution, especially on units that are supplementary fired, modeling and temperature monitoring are recommended.

6.3.1.1 Flow Modeling

A three dimensional physical flow model should be constructed to help analyze expected flows. The model data should be used to determine the optimum arrangement of the equipment and the shape and location of gas distribution devices, if any, to obtain desired temperature and flow limits, CO catalyst and SCR operation through the load range and to minimize pressure losses. The model scale should be no less than 1 to 12.

Numerical computer simulation may be considered as a supplement to the physical model to enhance the cost effectiveness of evaluating multiple configurations. Numerical modeling may be especially appropriate for evaluating gas temperature distribution before and after the burner, each section and the CO catalyst. Numerical simulation may also be considered as an option, but not as an alternative, to the physical model. If numerical computer simulation is proposed, it should be shown that there is previous validation between the proposed numerical simulation model and actual field experience on similar gas mixing and distribution problems.

As a minimum, the objectives of the modeling should be:

- To determine the optimum arrangement of the equipment, and the shape and location of gas distribution devices necessary to obtain uniform gas flow conditions through the load range, and to minimize pressure losses.
- The velocity profile at the upstream face of the first section into the HRSG should meet at least the following minimum requirements once all flow distribution devices are included in the model:
 - 85% (or more) of the measured velocities are within 10% of the root mean square (RMS) velocity and temperature for the cross section.
 - 15% (or less) of the measured temperatures and velocities are between 10 and 15% of the RMS temperature and velocity.
 - 100% of the measured temperatures and velocities are within 15% of the RMS temperature and velocity.

6.3.1.2 Temperature Monitoring

Connections should be provided just downstream of the CT interface near the permanent inlet duct thermocouples. The connections should be for insertion of, and support of, a temporary thermocouple grid to be used during HRSG performance testing should the need arise. The temporary thermocouple grid elements should also be provided upon request. The grid should consist of stainless steel pipes arranged to establish a grid of measurement points (on the order of 24 locations).

Each heat exchanger section (from HP superheater to economizer sections and feedwater heaters, if provided) should be designed with test connections on the gas side inlet and outlet to measure gas side temperatures and pressures. The temperature probe pipe should extend at least 1 m (3 ft) into each module and be provided with thermocouple support, including radiation shield. Pressure taps connections should be designed in.

6.3.2 Pressure Levels

Generally, large combined cycle systems employ three pressure level HRSG designs. This permits initial generation at relatively high pressure levels with HP ST throttle pressures of > 12.4 MPa (1800 psig) and a single reheat thermal cycle. Steam temperatures can be at 565°F (1050°F) without the use of supplementary firing. With LP pressure level of < 0.69 MPa (100 psig) and condensate return temperature of < 38°C (100°F), the flue gas temperature at the stack with the CT firing natural gas can be lower than 93°C (200°F) without supplementary firing and less than 85 - 88°C (185 - 190°F) with natural gas supplementary firing, thus capturing all of the practical useful energy from the exhaust stream without jeopardizing components to dewpoint corrosion. Using sulfur bearing fuels the minimum stack temperature is usually controlled in the range of 93 - 177°C (200 - 350°F) with heat exchanger design or bypass of feedwater preheater and LP economizer sections.

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6.3.3 Pinch and Approach Temperatures

For optimum thermal efficiency and design economy, the HRSG must incorporate pinch and approach temperature levels that allow for the cycle employed and the mode of operation (base load or cycling). Pinch temperature is defined as the differential between the flue gas temperature *leaving* the evaporating sections and the saturation temperature at the respective operating pressure. This defines the amount of steam generation. The approach temperature is the differential between the saturation temperature and the economizer outlet water temperature. This parameter is important as it is an indicator of the potential for economizer steaming; a condition that is prone to occurring during load cycling, which can cause thermal fatigue and other tube failure mechanisms, in addition to causing operating problems in drum level control and water hammer in HRSG piping systems. Generally, cycling units are designed with higher approach temperatures than base loaded installations to prevent these problems. The superheater approach, as the name implies for a counter current design section, is the difference between the minimum flue gas temperature and the superheater outlet steam temperature. Typical values for these parameters are: Pinch Point: 11.1 - 27.8°C (20 - 50°F), Economizer Approach: 5.6 - 16.7°C (10 - 30°F), and Superheat Approach: 22.2 - 33.3°C (40 - 60°F).

6.4 Gas Side Condensate Management

Action 6.4a *Incorporate design practices to minimize or eliminate condensation during operation.*

Rationale: *Condensing of constituents contained in flue gas of a HRSG is always a cause for concern. In addition to contributing to fouling, which increases back pressure on the CT thus affecting the cycle efficiency and output, the heat transfer and pressure part temperature profiles can change appreciably. Further, the depositing substances may be corrosive.*

Potential HRSG Damage: *Gas-side pitting and corrosion, acid dewpoint corrosion and stress corrosion cracking.*

There are several gas side condensation issues of concern in regards to HRSG damage types. The primary topic of discussion in this section is the potential for cold end or dew point corrosion. The potential for corrosion caused by ammonia slip of SCR systems and the subsequent formation of ammonium bisulfate is discussed in Section 6.5.

6.4.1 Cold End Corrosion

Action 6.4b *Evaluate whether cold end temperatures, in conjunction with expected level of contaminants, and alloy choice, are likely to result in significant deposition and corrosion.*

Action 6.4c *Determine the appropriate corrosion allowances or methods for mitigating that corrosion.*

Action 6.4d. *Ensure that proper material choices are made for low temperature sections.*

Rationale: If operating temperatures in the economizer, or water heater tubes fall below the acid dew point temperature, corrosion could occur as a result of the condensation of sulfuric acid and water vapor from the flue gas.

Potential HRSG Damage: Acid dewpoint corrosion in the final tube rows, exhaust ducts, and stacks.

According to a survey performed by Bourgeois [6-10], the exhaust stack gas temperatures in HRSGs have been steadily decreasing and most manufacturers anticipate a continued decrease for future designs. The high, average and low exhaust stack gas temperatures on natural gas fired units are expected to be 93°C (200°F), 76°C (169°F), and 45°C (113°F) by 2005. For oil or naphtha firing, the stack temperature is customarily 121-149°C (250-300°F). This downward trend in exhaust gas temperatures is expected to result in an increase in the potential for dew point corrosion. Unless corrosion resistant materials are used or special design alterations are made the acid and water vapors of either natural gas or oil fuels will condense on and corrode these back end components.

During combustion, sulfur in the fuel is released and oxidized to sulfur dioxide (SO_2). A small amount (in the range of 1 to 5%) of the sulfur dioxide is further oxidized to sulfur trioxide (SO_3) [6-11]. The oxidation of SO_2 to SO_3 in combination with water vapor forms sulfuric acid. When temperatures are lowered to the dew point, the sulfuric acid condenses, and forms a low pH electrolyte that is capable of generating rapid corrosion rates in excess of 12.5 mm/yr (0.5 inch/yr) and exacerbating the fouling of the affected surface.

The temperature at which condensate first appears depends upon a number of factors; however, for a 10 ppm SO_3 concentration, the dew point is about 140°C (~285°F). If feedwater temperatures are above this temperature and SO_3 levels are usually below 10 ppm, low temperature corrosion of tubing is seldom encountered.

A number of parameters can affect the rate of acid dew point corrosion in these components where the normal operating temperatures can be around the acid dew point. These factors include: fuel type, excess oxygen level, moisture level, surface temperature, and the presence of a catalyst that serves to oxidize SO_2 to SO_3 . Recent data suggests that SO_3 concentration can double, which correspondingly raises the acid dewpoint temperature. The HTF manual [6-2] contains a complete discussion of the mechanism and its mitigation.

Gas firing, because there is little or no sulfur and ash in the fuel, generally has a low dew point, low concentrations of acid vapors and a low potential for corrosion.

Oil firing produces a greater potential for corrosion and at a higher temperature [6-12]. The back end components of oil fired boilers can be susceptible to low temperature corrosion because of the presence of vanadium in the fuel ash which is a good catalyst for converting SO_2 to SO_3 and because of the small quantity of ash, which can serve as a buffer, in the flue gases.

There is a peak in the rate of acid deposition depending upon temperature, which various investigations have found to be within the range 22°C to 55°C (~40°F to 100°F) below the dew point [6-13, 6-14, 6-15, 6-16].

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Design steps to prevent this problem will involve providing the means to raise the gas and metal temperatures above the acid dew point or lowering the acid dew point; the latter has far more options available [6-2].

6.4.2 Potential for Stress Corrosion

Action 6.4e *For HRSGs having components fabricated with austenitic stainless steel, ensure that the water source for aqueous ammonia reagent use in SCRs does not contain chlorine or chloride salts.*

Rationale: *Austenitic stainless steel is very susceptible to stress corrosion cracking when under tensile stress and exposed to dilute or concentrated constituents (particularly sodium or chlorides) in the liquid phase at relatively low temperature. Attack is quick and very destructive. The feedwater preheater section is most at risk as it is usually fabricated from alloy steel.*

Potential HRSG Damage: *Tube failures in the feedwater preheater section or failure of finning material resulting in performance deterioration.*

The use of 19.5 or 29.5% NH_3 diluted aqueous solutions as reagents in HRSG SCRs is achieved by mixing with water. It is common for the water used to be a municipal water source that likely contains chlorine for controlling bacteria levels.

Since feedwater preheaters are normally fabricated with high alloy steel to protect against pitting corrosion by oxygenated water, the materials of construction may be susceptible to other corrosion processes. Series 300 stainless steel, for example, is prone to attack from stress corrosion cracking when it is exposed to certain constituents and under certain circumstances. The common corroding agents are usually sodium compounds and chlorine. The conditions required are a member under tensile stress that is operating at a temperature of $\sim 200^\circ\text{F}$ (94°C) exposed to a liquid phase solution.

If any components located downstream of the SCR is fabricated with austenitic stainless steel, then the use of aqueous ammonia should be evaluated carefully to ensure no chlorine exists in the solution. If there is chlorine present, an alternative material selection that is much more resistant to this failure mechanism is Series 400 ferritic or duplex stainless steels.

6.4.3 Fouling

Action 6.4f *Take care in specifying fin spacings if fuel oils are likely to see significant use.*

Rationale: *The predominant use of finned tubing makes HRSG tubes susceptible to fouling when burning some fuel oils. External tube deposits (on finned or unfinned tubes) will affect the heat transfer to the tube. Cleaning techniques are difficult to implement and may be costly.*

Potential HRSG Damage: *Fouling of heat transfer surfaces.*

Additional guidance on fin spacing is provided in Section 6.2.2

6.5 HRSG Considerations Related to Emissions Control

Permitted emission levels are strict for new units. There are several emissions control decisions that have the potential to cause damage in the HRSG. Discussed in this section are: water/steam purity requirements for controlling NO_x (subsection 6.5.1), potential for ammonium sulfate corrosion (subsection 6.5.2), and HRSG considerations and emissions on startup (subsection 6.5.3).

6.5.1 Water/Steam Purity Requirements for NO_x Control

Action 6.5a. *Determine purity requirements for water or steam used to reduce NO_x levels.*

Rationale: *Water injection to the CT for NO_x control can carry contaminants into the HRSG. These contaminants include solids, which over time can deposit and foul the finned tubes. Alkalis such as potassium and sodium also produce compounds that foul and corrode tubes and are deleterious to performance.*

Potential HRSG Damage: Gas side corrosion and pitting

Many combustion turbines require large quantities of water or steam to reduce NO_x emissions (and/or to increase power output of the combustion turbine/generator). This requirement has, however, been eliminated on many recent combustion turbines when firing natural gas. Some oil fired combustion turbines also may have dry NO_x control. The water or steam must be sufficiently pure to prevent deposition on, and corrosion of, the combustion turbine.

Limits for water or steam used for NO_x control from various combustion turbine manufacturers can be found in Appendix A of Ref. [6-17]. The sodium and potassium limits are quite stringent because compounds of sodium and potassium are very corrosive to combustion turbine components [6-18]. These same limits are also prescribed for sodium and potassium in the fuel used to supply the combustion turbine. Because the quantity of water or steam injected into the combustor can be greater than the quantity of fuel used, the maximum levels established for sodium and potassium in the steam or water are such that the sum of contaminants does not exceed the maximum level permitted in the fuel alone. Some manufacturers recommend that the normal level should not be exceeded when burning oil; however, the maximum levels are permitted when burning gas [6-18].

Maximum levels have also been established for heavy metals, although their levels would be expected to be low if sodium and potassium limits have been met [6-18]. Silica, magnesium, and calcium, while not corrosive, can significantly increase gas turbine blade fouling. Generally, the quality of injected steam or water should be largely the same as for the quality of steam required by a steam turbine [6-18].

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6.5.2 Potential for Ammonium Sulfate Corrosion

Action 6.5b *Evaluate methods for minimizing ammonium sulfate formation if it is anticipated that sulfur bearing fuels will be fired.*

Rationale: *Ammonium sulfates can cause significant fouling of heat transfer surfaces and have the potential for corrosion of HRSG tubes.*

Potential HRSG Damage: *Gas side fouling and corrosion of tubes.*

Selective catalytic reduction (SCR) systems are used to reduce the levels of NO_x produced by firing fossil fuels. Most of the U.S. experience with SCR systems has been in units firing natural gas and where sulfur is limited, and this has led to few gas side problems in HRSG units. However, HRSG units firing sulfur-bearing fuel oils, even for short periods of time, have had problems with fouling caused by deposition of ammonium salts, particularly ammonium bisulfate and ammonium sulfate. Ammonium bisulfate is produced when unreacted ammonia used in SCR (so called “ammonia slip”) combines in a flue gas environment with SO_3 and water vapor to form NH_4HSO_4 .

Operating within NO_x , CO and ammonia slip requirements requires individual equipment component operation, performance balancing and control logic tuning to meet the permitted levels. For example, reducing combustion turbine NO_x can increase CO. An increase in NO_x emissions increases the need for selective catalytic reduction (SCR) performance and can result in increased ammonia slip.

SCR reactor systems using ammonia as the reagent are designed for optimum NO_x reaction in the 288 - 427°C (550 - 800°F) range. They can produce an excessive quantity of ammonium bisulfate that deposits on metal surfaces at temperatures in the range of 149 - 190°C (300 - 375°F). SCR reactors are normally located downstream of the HP evaporator section in large triple pressure units. Therefore, there is a significant quantity of finned surfaces located downstream that is susceptible to fouling.

The effect of excessive ammonia slip and or the use of sulfur bearing fuels exacerbate the problem. This, combined with today’s HRSG designers pushing the envelope with regard to fin spacing – now up to 3 fins per cm. (7.5 fins per in.) in certain sections – increases the risk of pressure drop increase, irreversible fouling, maldistribution of flue gas and a contributing factor to a host of tube failure mechanisms. Figure 6-7 [6-19] depicts the comparison of a clean tube with one fouled with ammonium bisulfate deposits.

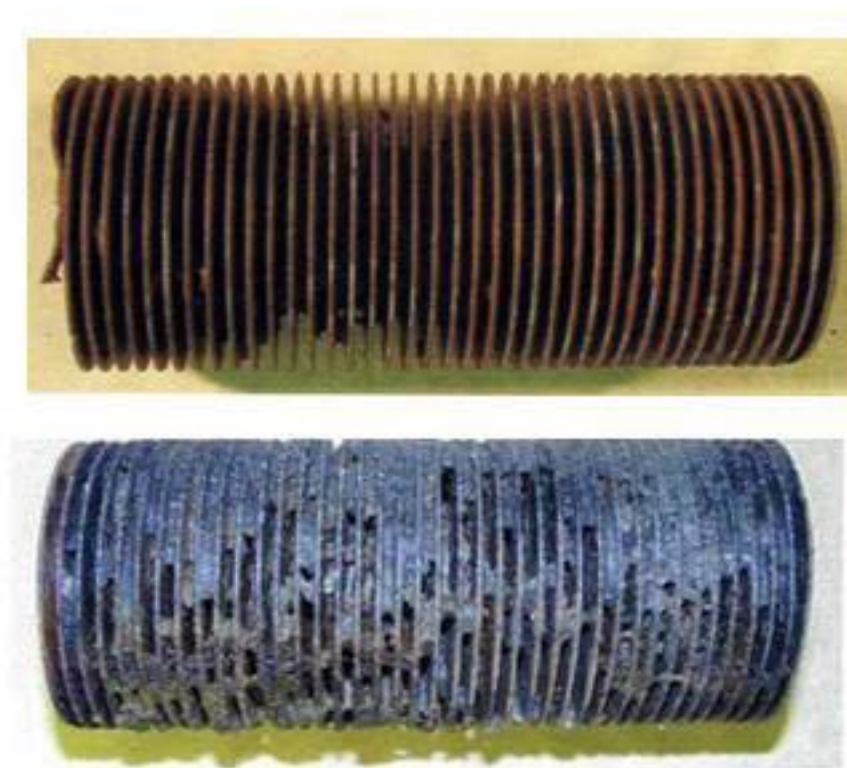


Figure 6-7
Comparison of clean HRSG tube with one fouled with ammonium bisulfate [6-19].

6.5.3 HRSG Considerations and Emissions on Startup

Action 6.5c *During cold starts, hold the CT at minimum output to heat soak the HRSG.*

Rationale: *Excessively rapid loading in an attempt to quickly achieve air permit compliance will cause fatigue damage in the HP superheater, reheater and HP drum.*

Potential HRSG Damage: *Fatigue mechanisms, especially thermal and creep.*

When applying for air permits, a common error is to assume that during cold starts the CT will be loaded as quickly as the CT vendor will permit to about 50% CT load in order to get into compliance with the CT in dry-low NO_x mode as quickly as possible. In order to avoid excessive fatigue life expenditure during cold starts in HRSG HP superheater, reheater and HP steam drum, it is important to hold the CT at minimum output of about 5% with the practical minimum CT exhaust gas temperature, typically about 370°C (700°F), for heat soaking the cold superheater. There should also be operation with minimum gas flow temperature and to minimize the heat input to the HP evaporator during initial pressure raising when the rate of increase in HP saturation temperature with pressure is very high. The time required during cold and warm starts to get into compliance with air permits is strongly influenced by steam turbine heating rates and by the time required to obtain acceptable steam quality before the ST is rolled.

Design: Gas Side

The pressure and steam temperature requirements of the HRSG can be accommodated in this overall time set by the ST.

The foregoing concern applies to cold starts and to cool/warm starts of the HRSG. Provided the HP pressure remains high enough after an overnight offload period for the restart to be a hot start for the HRSG, the CT can be reloaded to 50% CT output relatively soon after synchronizing the CT. Some steam turbines also impose additional constraints during hot starts. See Section 4.3 for a discussion of key considerations during unit startup and shutdown.

6.6 References

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7

DESIGN: GLOBAL AND LOCAL STRESSES

7.1 Overview of this Chapter

The stresses experienced by HRSG pressure parts determine the achievable lifetime of each component. Of interest is the total stress state, including applied stresses (thermally-induced, weight, pressure, and vibration), as well as residual stresses developed by fabrication, welding, supports, and restraints or guides. The local stress state is further affected by geometry of the joint and the resultant stress concentrations.

While it is not possible to review all relevant topics pertaining to the development of stresses in HRSG pressure parts, an attempt has been made to provide a discussion of the most critical, particularly the subtle issues surrounding thermally induced transient stresses that are of crucial importance for HRSGs intended for cycling service.

The chapter begins with a short overview of transient thermal stresses and their impact on the HRSG reflecting the importance of this particular source of stress (Section 7.2). International boiler codes have limitations in their coverage of thermally induced stresses; this issue is described in Section 7.3.

Subsequent sections look at specific sources of these critical thermal stresses including:

- Thick-section components - headers and drums (Section 7.4).
- Tubes and their attachment to headers (Section 7.5).
- Differential expansion of tubes and panels (Section 7.6).
- Formation of condensate and inadequate design and improper operation of drains in superheaters/reheaters (Section 7.7).
- Row-to-row tube temperature differences in HP superheaters and reheaters during startups (Section 7.8).
- Performance of HP superheater and reheater attemperators (Section 7.9).
- Sources in evaporators (Section 7.10).
- Economizer venting, steaming and support issues (Section 7.11).
- Shared headers in economizers (Section 7.12).
- Startup flows in economizers (Section 7.13).
- Recirculation in economizer and preheater tubes (Section 7.14).
- Drains in evaporators and economizers (Section 7.15).

Geometric stress concentrations and the effect of layout arrangements are addressed in Section 7.16. Panel and module support arrangements are discussed in Section 7.17. The final section, Section 7.18, examines another source of stresses, vibration, and looks at design steps that can help minimize that problem and the attendant noise.

7.2 Importance of Transient Thermal Stresses

Action 7.2 *Identify and evaluate the potential sources and enhancers of thermally-induced stresses in HRSG circuits and apply the appropriate design features to mitigate them.*

Rationale: *To prevent excessive transient and steady state thermal stress in HRSG pressure parts of all circuits.*

Potential HRSG Damage: *Primarily thermal fatigue, creep fatigue and corrosion fatigue.*

The susceptibility of the pressure parts of HRSGs to high thermally induced stresses during shutdowns and startups has been identified as a major threat to their reliability and durability, especially if the combined cycle unit is to be subjected to some cycling operation [7-1, 7-2].

Three specific tube failure mechanisms, thermally-induced fatigue, creep fatigue and corrosion fatigue, can be caused by high thermally induced cyclic stresses at tube attachments to headers.

Thermally induced bending stresses at attachment welds to headers are usually highest on the outer surface at the toe of the weld attaching a tube to a header. Cyclic thermal bending stresses will initiate and propagate low-cycle, high-strain fatigue cracks through the tube wall from the outer surface of the weld, or sometimes on the outer surface at the extrados or intrados of small-radius bends at the tube- to-header attachment. Thermally induced fatigue cracks grow from outside to inside surface of the tubes.

Corrosion fatigue cracks grow through the tube wall from inside to outside. Depending on the type of weld preparation, and also on the quality of the weld root pass, it is possible for the thermally-induced cyclic bending stresses to initiate and propagate corrosion fatigue cracks at internal stress-concentrating features, such as weld root defects or the notch of partial penetration welds. Corrosion fatigue also occurs a short distance from the inlet to water-wetted tubes where bending stresses are high and the vena contractor phenomenon is believed to create a localized corrosive environment.

Premature thermally-induced fatigue failures have occurred at tube attachments to headers in some HRSG designs; in some cases before 200 startup-shutdown cycles. These are quite likely the forerunner of more widespread failures as other large HRSGs with somewhat less severe designs accumulate larger numbers of starts. For example, if the cyclic stress range at tube attachment welds to headers is assumed to be half that experienced by HRSGs which exhibited failed economizer or superheater tubes before 200 starts, then widespread failures would be expected before 2,000 starts. For units intended to perform cycling service with several thousand starts, the maximum cyclic stress range would need to be less than 25% of those experienced by units that have exhibited failures before 200 starts.

Thermally induced fatigue and corrosion fatigue failure mechanisms can both be prevented by avoiding significant thermally induced stresses at tube attachments to headers. To accomplish this objective, the HRSG design must (i) prevent significant transient temperature differences between tubes attached to the same upper and lower headers, (ii) avoid tube, header and piping arrangements that cause significant forces and bending moments at tube attachments to the headers; (iii) avoid tube-to-header connection designs which excessively concentrate the applied forces and moments; and (iv) ensure that the CT exhaust gas characteristics during startup and initial loading, and the methods used during deloading and shutdown of the CT, do not develop large transient temperature differences between tubes and headers. More detail about the first three items is discussed throughout this chapter. Detail about the effects of CT exhaust gas characteristics can be found in Section 4.5.

7.3 Overview of Analysis Methods for Thermally Induced Stresses and the Role of International Steam Generator Design Codes

Action 7.3: *Understand that common international steam generator codes may not provide adequate guidance for some key design issues; require suppliers to provide the design basis for critical calculations.*

Rationale: *Prevention of fatigue-related failures requires the use of guidance from multiple international boiler and pressure vessel codes and sophisticated analytical modeling to establish cyclic stresses and conservatively predict component cyclic life expenditure rates.*

Potential HRSG Damage: *Creep fatigue, thermal fatigue, corrosion fatigue.*

Problems have arisen with HRSG pressure parts because owners have assumed that they can rely on boiler design codes to ensure the longterm reliability of the HRSG, no matter what its operating regime. At the present time, none of the steam generator design/construction codes that have widest international use adequately address underlying design weaknesses that have been the root causes of persistent failure mechanisms in tubes and headers of conventional boilers and HRSGs. None of the most widely used codes provide guidance on the methodology for evaluating thermal stresses in tubes caused by transient temperature differences between the tubes attached to the same header, or between the tubes and header at the tube attachment weld, during startups and shutdowns. As a result, the purchaser and the HRSG vendor need to ensure that reliable stress and design life analyses based on conservative assumptions of the temperature differences and resultant stresses in tubes and interconnecting pipes of all sections of the HRSG have been performed.

A few HRSG vendors routinely use in-house design methods that include dynamic simulations of tube temperature transients during startups. The results are then input into sophisticated thermal-mechanical analytical models for each HRSG module to calculate peak stresses in tubes, supports and interconnecting pipes. However, other HRSG vendors rely largely on past unit design experience. That experience may not be sufficient as design conditions continue to become more demanding on the materials of construction.

7.3.1 ASME Boiler and Pressure Vessel Code (Section I, Section VIII, Div. 1, and Subsection NH of Section III)

The most widely specified boiler code, the ASME Boiler and Pressure Vessel Code, Section I, Power Boilers, has serious omissions in respect to component life assessment. Strict compliance with the requirements of the ASME Boiler and Pressure Vessel Code, Section I, Power Boilers, will not be sufficient to ensure that the HRSG will provide 20 or 30 years of reliable service regardless of the operating regime to which the combined cycle unit is subjected. The ASME Boiler and Pressure Vessel Code, Section I, Power Boilers, does not give guidance to either the determination or limitation of transient stresses that are developed in the HRSG pressure-part components during shutdowns and startups.

The ASME Code specifies allowable design stresses for a single, notionally 100,000-hour design operating life. The advent of deregulation in the electricity industry has prompted an increasing demand from purchasers for combined cycle plants to be designed for 30 years of reliable cycling service (i.e. for 150,000 service hours with 7,500 overnight unit shutdowns or 200,000 service hours with 4,500 overnight shutdowns). However, the ASME Boiler Code provides no data to enable the steam generator parts subjected to creep conditions to be designed for specific service hours, or to determine the further reduction in allowable stresses necessary for parts subjected to fatigue or creep fatigue interaction during a design service life that includes specific numbers of cold, warm and hot start-shutdown cycles.

For unfired pressure parts that operate below 371°C (700°F), ASME Section VIII Division 2 provides a method for evaluating cyclic conditions to determine when a fatigue assessment is required. The rules set forth the conditions under which a comprehensive fatigue analysis isn't needed. The method is conservative, provided there are no abnormal stress-concentrating features and provided the internal surfaces in contact with the fluid are not subjected to high heat transfer rates in conjunction with rapid changes in internal fluid temperature. The methods may be non-conservative for thick-walled HP steam drums that can develop very high, non-linear temperature gradients at the inner surfaces during pressure raising and decreasing ramps. These design rules are not appropriate (i) for fired HRSGs, (ii) for HP superheater headers subjected to temperatures greater than 371°C (700°F) or (iii) to components subject to condensation heating or quench cooling during shutdowns and hot restarts.

Subsection NH of ASME Section III, Division 1 provides rules for performing creep fatigue assessments. Although these are generally regarded as conservative, there are concerns that, for components of low alloy ferritic steels which happen to have a predicted creep life at steady state operating conditions of less than 12%, the interaction diagram in Appendix NH is non-conservative when the material creep strain rate at the high temperature dwell part of the thermal cycle is high. Pending further investigation of this issue, it is recommended that an upper limit of about 10% is specified for the design fatigue life expenditure of parts that operate at temperatures well into their creep range.

7.3.2 German TRD301

The German "Technical Rules for Steam Boilers", TRD 301, does include a mandatory fatigue assessment by the calculation method set out in its Annex 1. The method of calculation

addresses (i) cyclic loading due to internal pressure pulsations, (ii) the combined changes of internal pressure and temperature, and (iii) the thermal-mechanical forces and moments applied cyclically at tube and pipe connections to headers and manifolds.

For pressure part components that operate with a maximum temperature below about 400°C (750°F), TRD301 is generally considered to be a conservative method for assessing cyclic life, provided there are no abnormal stress concentrating features or high heat transfer rates.

However, where headers and manifolds are subjected to condensation heating or quenching by subcooled condensate, TRD301 may be non-conservative and finite element analysis, validated with measured transient temperature characteristics, is recommended.

For components such as pressure parts in contact with water, which are manufactured from non-austenitic steels, special design requirements are set out in TRD Annex 1, Paragraph 5.1.4. These design rules limit the estimated applied strain to values which, in general, will prevent cracking of the oxide scale which forms on the water-touched surfaces, thus preventing corrosion fatigue damage. It is recommended that these special design rules be required for all water-touched HRSG pressure parts. A more detailed discussion of these rules and an overall state-of-the-art to addressing corrosion fatigue can be found in Reference [7-8].

For components that operate significantly above 400°C (750°F), TRD301 does not fully account for creep fatigue interaction and is significantly less conservative than Section NH of ASME Section III, Division 1. For HRSGs intended for extensive cycling service, the more prudent practice adopted by some has been to limit the design fatigue life expenditure in those parts which experience relatively high creep at the high temperature dwell part of their thermal cycle to about 10% to conservatively account for creep fatigue interaction. For headers of moderate thickness (less than 40 mm (~1.5 in)), this can usually be achieved without adding to the overall duration of the CT/HRSG restart from hot and warm initial conditions.

7.3.3 European Norms EN 12952 (Water-Tube Boilers and Auxiliary Installations), prEN 12953-3 (Shell Boilers – Part 3: Design and Calculation) and prEN 13445 (Unfired Pressure Vessels)

In 1997, the European Union legislated a Pressure Equipment Directive (PED), which has been implemented and is now mandatory in most European Union member countries. Standards for boilers are provided in the European Norms, some of which have yet to be issued. EN 12952-3, Section 13, incorporates a fatigue assessment and calculation method for steam and water-touched pressure parts. The fatigue assessment is based on that previously set out in TRD 301, including the special corrosion fatigue requirements for non-austenitic, water-touched components, but has incorporated some additional guidance from other European codes. It appears that prEN 12952-3 does not fully account for creep fatigue interaction and is significantly less conservative in this respect than Section NH of ASME Section III, Division 1. For HRSGs intended for cycling service the prudent practice adopted by some has been to limit the design fatigue life expenditure, as calculated by EN 12952-3, in those parts which experience relatively high creep at the high temperature dwell part of their thermal cycle to about 10% to conservatively account for creep fatigue interaction.

7.3.4 British Standards BS1113 and BS5500

The British Boiler Code, BS1113, includes cautionary advice that cyclic thermal-mechanical loads and stresses should be assessed and refers to methods for assessment of cyclic life in BS5500, the Unfired Pressure Vessel Code. However, a fatigue assessment is not a mandatory requirement of BS1113, which leaves it to the purchaser to agree with the vendor whether an assessment is required, and the methodology for performing any fatigue assessment. In consequence, it is unusual for fatigue assessments to be performed. The British Boiler Code does provide allowable stresses for a wide range of alternative design operating hours, facilitating life assessments of all components, including those higher temperature parts subjected to fatigue degradation.

BS1113 is being replaced by EN 12952. However, some of the fatigue assessment methods and the data on weld fatigue strength reduction factors incorporated in BS5500 will continue to be utilized in fatigue assessments of weldments.

7.3.5 Further Guidelines Required for Performing Creep Fatigue Assessments

The absence of a generally accepted set of rules for performing prudently conservative fatigue life assessments, and the significant discrepancies in the results obtained by the different rules that are presently available, is a handicap to the development of reliable HRSG pressure part designs for cycling service. New EPRI guidelines are planned that will provide guidance and rules for performing fatigue and creep fatigue life assessments of HRSG pressure parts.

7.4 Global Transient Stresses in Thick-Walled Components

Action 7.4a *Minimize header thickness by selection of the highest strength from available suitable materials. Minimize the diameter of critical headers, which also contributes to reduction in header thickness.*

Rationale: *In combination, these actions substantially increase the cyclic life of critical headers before initiation of cracks at their inner surface by tube holes. Minimization of the thickness of headers significantly increases the rate of response of the bulk mean wall temperature of the header. This minimizes the tube-to-header and through-wall header temperature difference and substantially increases the cyclic life of the tube at the toe of the attachment weld to the header and at the header borehole surfaces.*

Potential HRSG Damage: *Thermal fatigue or creep fatigue in headers and at the toe of the tube-to-header weld.*

Large and rapid changes in fluid temperature inside tubes and headers cause high thermal gradients within the composite structure comprising the header wall, tube wall and the weldment. These high thermal gradients develop peak stresses at two locations:

- The intersection of the tubeholes through the header wall with the header bore surface.
- The toe of the weld at the tube wall that rigidly connects the tube to the header.

Both locations are potential sites for premature thermal fatigue or creep fatigue, unless the design of the headers minimizes the thermal stresses caused by large, rapid changes in fluid temperature in the tubes and headers.

The rate of heating that the headers of HP superheater and reheater can safely accommodate without premature creep-fatigue failures is strongly influenced by their thickness. It is also influenced significantly by header diameter, because larger diameter headers require increased wall thickness and heat conduction from the tubes is a significant contributor to the heating of the header. In order to minimize header diameter, and thus its wall thickness, without compromising the uniform distribution of fluid through each tube, the inlet and outlet headers may need to be designed with several inlet and outlet pipe branches, each pipe branch handling the fluid from a smaller proportion of the tubes. Reducing the header thickness and diameter will have positive operating benefits as the startup time required to reload the CT to the output required for compliance with air permit emission limits without causing excessive creep fatigue damage in the HRSG will be significantly shortened.

Damaging transient thermal gradients in the headers occur because of the relatively rapid change of temperature of the surfaces of the headers in direct contact with steam, condensate or feedwater, compared to the much slower rate of change in the bulk mean temperature of the header material. Thermally-induced strains develop in those parts of the material that are prevented from expanding (or contracting). Compressive thermal stresses develop at the inner surface during heating; tensile thermal stresses during cooling. The thermally induced strains are proportional to the difference in temperature of the inner surface and the mean temperature of the bulk of the header wall thickness of the material.

Determination of the thermal transients has to be performed on a case-by-case basis because it is significantly influenced by several factors. These include the CT exhaust gas characteristic during startup and initial loading of the CT, the header thickness and diameter, the tube thickness and diameter, the number of tube rows attached to the header and the pitch between tubes, materials, any additional loading mechanisms at the tube attachment to the header that occur simultaneously, such as bending moments in offset tubes in panels with more than one row of tubes per upper and lower header, etc. Table 7-1 provides an example of the influences of header thickness and CT exhaust temperature on the number of cycles to crack initiation.

Actual tube and header transient temperature measurements were used as the starting point for the analysis presented in Table 7-1. From these the thermal stress at the toe of the weld attaching the tubes to the header was calculated and subsequently used to predict the number of cycles to crack initiation in the tube at the weld. Two estimates of cyclic life have been made. The estimates described in Table 7-1 as “Conservative” assume a step change in temperature between the tube and header and include both thermal bending stress and hoop stress caused by the temperature step. The estimated cycles described as “More realistic” have assumed that conduction from the tubes into the header develops a temperature gradient along the end of the tube and there will be no step change in temperature at the point of attachment. The thermal stress used to predict the “more realistic” cyclic lives assume the thermal hoop stress is zero. Note that this example is provided to give an indication of the benefits of lower CT exhaust temperatures and thinner header designs, it is not meant to be definitive of a particular HRSG unit or design.

Design: Global and Local Stresses

The cyclic life calculations in Table 7-1 indicate that a 51 mm (2 inch) thick header will consume a significant portion of the life of the tube attachment at the header during a few hundred colds starts, even for the more moderate CT exhaust gas temperatures. In contrast, the tubes attached to the 29 mm (1.16 inch) thick headers appear to be suitable for cycling service provided the CT exhaust temperature during the initial heat soak of the HRSG is limited to somewhat more than 371°C (700°F). Tubes attached to the header of 17 mm (0.68 inches) thickness have substantial margin on cyclic life.

For headers significantly thicker than 25 mm (1 inch), the peak transient tube-to-header temperature difference can be reduced by wrapping the bare tube ends with insulation. This would significantly reduce the fatigue life damage increments at the tube attachment to the header for the first few rows of tubes that experience the higher gas temperature during startups.

Horizontal Gas Path (HGP) and Vertical Gas Path (VGP) HRSGs are equally vulnerable to damage caused by the development of high thermal gradients in thick-walled structures. Furthermore, the means of minimizing fatigue damage by appropriate design, and by correct methods of operation during shutdowns and startups, are generally applicable to both HGP and VGP types of HRSG.

Table 7-1
Impact Of Header Thickness and Minimum CT Exhaust Gas Temperature Used for the
Initial HRSG Heat Soak on Thermal Fatigue Cycles to Crack Initiation at Toe of Tube to
Header Weld

Minimum CT exhaust gas temperature during the initial HRSG heat soak	Type of startup / Initial HP pressure	Cycles to crack initiation at toe of tube to header weld								
		Header thickness 51 mm (2.0 inches)			Header thickness 29 mm (1.16 inches)			Header thickness 17 mm (0.68 inches)		
		Peak tube-to-header ΔT °C (Δ °F)	Conservative cycles to cracking	More realistic cycles to cracking	Peak tube-to-header ΔT °C (Δ °F)	Conservative cycles to cracking	More realistic cycles to cracking	Peak tube-to-header ΔT °C (Δ °F)	Conservative cycles to cracking	More realistic cycles to cracking
495°C (925°F)	Hot, 4.7MPa (700 psia)	211 (380)	1,700	3,300	183 (330)	2,700	5,200	139 (250)	>10,000	>20,000
	Warm, 0.6 Mpa (100 psia)	228 (410)	800	1,500	200 (360)	2,100	4,000	155 (280)	3,600	7,000
	Cold, 0 press 16°C (60°F)	367 (660)	280	550	322 (580)	400	7800	228 (410)	780	1,500
380°C (715°F)	Hot, 4.7 MPa (700 psia)	100 (180)	6,800	13,100	89 (160)	7,700	15,000	72 (130)	>10,000	>20,000
	Warm, 0.6 MPa (100 psia)	167 (300)	3,200	6,300	150 (270)	4,100	8,000	111 (200)	6,200	12,000
	Cold, 0 press 16°C (60°F)	306 (550)	460	900	283 (510)	580	1,100	222 (400)	1,400	2,600
320°C (610°F)	Hot, 4.7 MPa (700 psia)	56 (100)	>10,000	>20,000	50 (90)	>10,000	>20,000	44 (80)	>10,000	>20,000
	Warm, 0.6 MPa (100 psia)	161 (290)	3,500	6,600	144 (260)	4,500	8,700	100 (180)	6,900	13,200
	Cold 0 press 16°C (60°F)	278 (500)	620	1,200	239 (430)	1,100	2,000	172 (310)	3,300	6,100

Calculation assumptions :

Tubes are in the gas inlet row.

Header is the upper header.

Applies to gas inlet panels with a single row of tubes.

7.4.1 Superheater/Reheater Headers

The headers and manifolds most likely to have limited cyclic life in all current designs of HRSG are (i) some of the HP superheater headers, (ii) possibly some reheater headers, and (iii) the HP steam drum. HP superheater headers most vulnerable to creep-fatigue cracking are (i) the upper and lower headers of the final superheating section, (ii) the superheater headers immediately before and after the superheater attemperator, and (iii) the outlet section of the reheater.

The upper headers, which on most current designs of horizontal gas path type of HRSG are the final outlet headers, operate at the highest temperatures and experience the highest rate of change in steam temperature during startups. The lower headers operate at a somewhat lower temperature and experience somewhat less severe steam temperature changes during heating at startups. However, the lower headers do experience the most severe cooling transients by condensate run off from tubes during shutdowns and especially during prestart purges of a hot HRSG.

Since the mid 1980's, cracks propagated from the header bore by creep-fatigue have been a widespread problem in superheater outlet headers of coal-fired and oil-fired utility steam generators that necessitated premature retirement of many superheater outlet headers. Usually failed P22 or P11 superheater outlet headers for conventional steam generators were replaced with headers fabricated from P91 material, which has significantly higher creep strength permitting the thickness of headers to be considerably reduced, thereby substantially increasing their cyclic life.

Current designs of HRSG HP superheater operate at similar pressures, and equal or more onerous steam temperatures, than utility steam generators with prematurely failed superheater headers. Higher design temperatures significantly reduce the allowable stresses and result in thicker headers unless more sophisticated design arrangements and/or materials are used. Furthermore, the HP superheater and reheater headers of current designs of HRSG are subjected to more severe changes in temperature during combustion turbine (CT) startups and CT shutdowns than those experienced by conventional steam generators.

Although to date there have been no reports of internal cracking in superheater headers of large HRSGs, few, if any, have been inspected internally due to difficult access. It is quite likely that some HRSGs in earlier "F-class" combined cycle plants, with the thicker P22 HP superheater headers that have performed a few hundred shutdown-startup cycles with widely used shutdown and startup procedures, have already initiated and may be growing cracks from the inner surfaces of some higher temperature superheater headers. Normal shutdown-cold start cycles and trip-hot restart cycles are the most damaging types of cycle for the HP superheater headers; normal shutdown-warm start cycles are moderately damaging; and normal shutdown-"cool" start cycles somewhere between cold and warm, depending on how close to 100°C (212°F) the headers are when the CT is started.

Tables 7-2 and 7-3 illustrate the effect of thickness and operation on a typical HP superheater outlet header and a typical lower header of a final HP superheater panel, respectively. The cyclic life predictions in Tables 7-2 and 7-3 use are based on stress ranges calculated by the mandatory fatigue design method in the German boiler and pressure vessel code, TRD301, using

fatigue endurance data from ASME Section VIII, Division 2, but limiting fatigue life expenditure to 12% instead of 50% advised by TRD301. This conservatism is more in-line with the recommendations contained in Subsection NH of ASME Section III and other data sources. The life consumption predictions labeled “More realistic” in Table 7-2 have reduced the thermal stress concentration factor recommended in TRD301 of 2 to 1.5 to reduce conservatism in the design.

The data in Tables 7-2 and 7-3 should not be interpreted as generally applicable to all similar headers. Each case must be independently assessed taking into account the specific HRSG design details and the pressure and temperature conditions developed in the HRSG superheater during shutdown and hot, warm and cold startups of each specific installation. The data are merely intended to highlight the considerable impact of header thickness on relative cyclic lives for upper and lower superheater outlet headers of different thickness. The data in Tables 7-2 and 7-3 assume the same thermal stress concentration factor for all cases. In practice, headers of smaller diameter and thickness will have significantly lower thermal stress concentration than those of thicker headers of larger diameter. This and other factors increase the conservatism of the design life estimates presented for thinner headers.

The data in Tables 7-2 and 7-3 (and also Table 7-1) highlight the importance of limiting the thickness of HP superheater and reheater headers to about 25 mm (1 in.) for HRSGs intended for cycling service. Headers of 25 mm (1 in.) or less thickness impose no practical limits to the steam temperature ramp rate during startups and can be steam cooled during shutdowns at reasonably brisk rates. Thicker headers require progressively more stringent restrictions to the rate of change in HP steam temperature during all startups and also shutdowns if they are to be cycled without initiating and growing cracks in the headers. Alternatively, the tube to header configuration (i.e., thickness transition, weld and connection design, insulation, etc.) must be designed to accommodate the anticipated thermal-mechanical transients.

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Table 7-2

Influence of Header Thickness and Design Lifetime Numbers of Startups on the HP Steam Temperature Ramp Rates Acceptable HP Superheater Outlet Headers

HP super-heater outlet header wall thickness mm (inch)	HP steam temperature ramp rate			Percentage of damage necessary to initiate cracks at intersection of tubeholes and bore of header, expended at end of design life. (100% indicates crack initiation). (n/a indicates damage exceeds 100%)					
				Predominantly continuous operation 300 cold + 300 warm + 400 hot = 1,000 starts		Very occasional cycling 400 cold + 600 warm + 1,000 hot = 2,000 starts		Regular cycling for 2/3 of 30 year life 500 cold + 1,000 warm + 4,000 hot = 5,500 starts	
	Ramp up + ramp down °C/min (°F/min)	Heating ramp rate at startup °C/min (°F/min)	Cooling ramp rate at shut-down °C/min (°F/min)	Conser-vative	More realistic	Conser-vative	More realistic	Conser-vative	More realistic
76 (3.0)									
	10.8(19.5)	9.2(16.5)	-1.7 (-3)	100	50	n/a	100	n/a	n/a
	14.4 (26)	11.7 (21)	-2.8 (-5)	n/a	100	n/a	n/a	n/a	n/a
64 (2.5)	7.8 (14)	7.2 (13)	-0.6 (-1)	18	7	33	18	100	50
	10.6 (19)	8.9 (16)	-1.7 (-3)	33	17	75	42	n/a	100
	11.9 (21.5)	9.4 (17)	-2.5 (-4.5)	50	25	100	50	n/a	n/a
	15.8(28.5)	12.5(22.5)	-3.3 (-6)	100	50	n/a	100	n/a	n/a
	21.1(38)	15.5(28)	-5.6(-10)	n/a	100	n/a	n/a	n/a	n/a
51 (2.0)	11.1 (20)	8.3 (15)	-2.8 (-5)	17	8	42	25	100	50
	15 (27)	10.6 (19)	-4.4 (-8)	42	18	75	42	n/a	100
	16.7 (30)	11.1 (20)	-5.6 (-10)	50	25	100	50	n/a	n/a
	22.2 (40)	13.9 (25)	-8.3 (-15)	100	50	n/a	100	n/a	n/a
	29.4 (53)	21.1 (38)	-8.3 (-15)	n/a	100	n/a	n/a	n/a	n/a
38 (1.5)	20 (36)	13.3 (24)	-6.7 (-12)	18	8	42	25	100	50
	26.1 (47)	17.8 (32)	-8.3 (-15)	33	18	75	42	n/a	100
	29.4 (53)	21.1 (38)	-8.3 (-15)	50	25	100	50	n/a	n/a
	40 (72)	28.9 (52)	-11.1 (-20)	100	50	n/a	100	n/a	n/a
	52.2 (94)	38.9 (70)	-13.3 (-24)	n/a	100	n/a	n/a	n/a	n/a
25 (1.0)	44.4 (80)	30.6 (55)	-13.9 (-25)	18	8	42	25	100	50
	58 (105)	41.7 (75)	-16.7 (-30)	33	18	75	42	n/a	100
	67 (120)	50 (90)	-16.7 (-30)	50	35	100	50	n/a	n/a
	89 (160)	67 (120)	-22.2 (-40)	100	50	n/a	100	n/a	n/a
	119 (215)	89 (160)	-30.6 (-55)	n/a	100	n/a	n/a	n/a	n/a
17 (0.68)	94 (170)	67 (120)	-27.8 (-50)	18	8	42	25	100	50
	128 (230)	94 (170)	-33.3 (-60)	33	18	75	42	n/a	100
	144 (260)	106 (190)	-38.9 (-70)	50	25	100	50	n/a	n/a
	194 (350)	139 (250)	-56 (-100)	100	50	n/a	100	n/a	n/a

Table 7-3
Impact of Method of CT/HRSG Shutdown on Cycles to Crack Initiation at Bore of Lower Header of Final HP Superheater Panel as a Function of Header Thickness and Method Used for Normal Shutdowns

Lower header wall thickness mm (inches)	Estimated cycles to initiate cracking at the intersection of the tubehole with the bore of the lower header.					
	Fast CT shutdown		Extended CT shutdown method to steam cool the header before CT fuel shut off, as recommended in Section 4.5.2			
	With startup ramp of 28°C/min (50°F/min)	With startup ramp of 8°C/min (15°F/min)	Ramps: cooling -6°C/min (-10°F/min); heating 8°C/min (15°F/min)	Ramps: Cooling -8°C/min (-15°F/min); heating 17°C/min (30°F/min)	Ramps: Cooling -11°C/min (-20°F/min); heating 28°C/min (50°F/min)	Ramps: Cooling -17°C/min (-30°F/min); heating 56°C/min (100°F/min)
64 (2.5)	<<100	<<100	2,800	560	160	<<100
51 (2.0)	<<100	<<100	8,700	1,960	590	105
38 (1.5)	<100	130	32,000	8,400	2,800	520
25 (1.0)	820	1,230	135,000	50,000	20,000	4,500
17 (0.68)	6,100	8,700	330,000	168,000	87,000	27,000

Although lower headers typically operate at temperatures about 28°C (50°F) lower than in upper final outlet headers, they are susceptible to much more severe cooling shocks during CT deceleration, CT spin cools immediately after shutdown, and/or during a prestart purge of a hot HRSG during which condensation occurs in superheater tubes that quench cools the lower header. The cyclic life predictions for lower header in Table 7-3 compare the substantial creep fatigue life benefits of the lower header obtained by the “normal shutdown” procedure recommended in Section 4.3.2. This reduces the temperature of the lower header at a moderate rate close to saturation temperature by reducing the CT exhaust gas temperature and thus the HP steam temperature at a controlled rate before the CT is finally shut down. This is in contrast to the damaging effects to the HP superheater of the widely used practice of rapid unloading and prompt shutdown of the CT while maintaining high HP steam temperature.

7.4.2 Economizer/Preheater Headers

Action 7.4b *Install means to prevent shocking of hot LP economizer/preheater inlet headers by cold feedwater during startups.*

Rationale: *When drum swell subsides and feedwater is required to maintain drum levels, the sudden introduction of cold feedwater during startups thermally shocks the relatively hot LP economizer/preheater inlet headers and tubes, unless means are provided to raise the inlet feedwater temperature in a controlled manner.*

Potential HRSG Damage: *Thermal fatigue in headers, corrosion fatigue and thermal fatigue in tubes at attachment welds.*

During the shutdown, heat is convected from the hot HP section of the HRSG to the back section and the stagnant preheater/LP economizer can heat up to about 205°C (400°F) prior to the establishment of feedwater flow to the steam drums. The normal temperature of condensate supplied to the preheater/LP economizer may be about 38°C (100°F), which, without means of tempering, causes a thermal shock of up to about 166°C (300°F) to the inlet header and inlet row tubes.

Ligament cracking initiated from the bore by thermally induced fatigue has been persistent in some designs of economizer inlet headers in conventional utility boilers. High tensile stresses are caused by the rapid chilling of the inner surface of hot stagnant economizer inlet headers each time cool feedwater flow is initiated during overnight shutdowns and during startups to top the HP steam drum. The inlet headers of lowest temperature economizers are also subjected to rapid chilling during startup each time cold feedwater flow is initiated, which may occur several times per start on some installations.

For current designs of HRSGs, which usually have carbon steel economizer inlet headers, the thermal shock is less severe than experienced in economizers of conventional boilers. Analysis of temperature gradients measured on HRSG LP economizer inlet headers of about 25 mm (1 inch) thickness concluded that they are unlikely to develop thermal fatigue cracking from the inner surface of the headers due to transient through-wall temperature gradients developed by the thermal shock.

However, because the tubes attached to the header cool very rapidly to the temperature of the incoming cold water and the bulk wall temperature of the header responds much slower, there are concerns that the high header-to-tube temperature difference caused by a thermal shock of about 166°C (300°) may lead to thermal fatigue failures from the toe of the tube weld or to corrosion fatigue in the vicinity of the root of welds on units that are cycled extensively.

Long economizer inlet headers of older conventional boilers fed by feedwater from an end connection also experienced many tube failures due to thermal bowing when trickle-feeding during startup, caused by stratification of the initial cold water flow along the bottom of the hot inlet header. Most designs of economizers in HRSGs usually have a separate, relatively short inlet header for each module, each having one or more inlet pipe branches. However, to reduce cost some HRSGs have interconnected several low temperature inlet headers with the feedwater being supplied by a single end connection. This is likely to cause cyclic loads in the inlet row of tubes when admitting the initial flow of cold feedwater at each startup, unless means are provided to temper the incoming feedwater.

Alternative means used to avoid thermal shocks to preheater/LP economizers are the use of a condensate recirculation system and/or a separate, heated deaerator to raise the incoming feedwater temperature.

7.5 Development of Thermally Induced Stresses Caused by A Variety of Differential Tube Expansion Mechanisms

Action 7.5a: Utilize panels comprising a single row of straight tubes attached radially to the same pair of upper and lower headers.

Action 7.5b: *For panels that have two tube rows, perform stress analysis and cyclic life calculations for assemblies of panels, tubes, and interconnecting pipes incorporating the predicted peak transient temperature differences during startups and shutdowns from dynamic simulations.*

Rationale: *Temperature differences between tubes of a single row of straight tubes cause only direct thermally induced forces and stresses in the tubes. Panels comprising two or more rows of tubes per pair of headers inevitably develop much higher localized thermally induced stresses at attachment welds due to the additional bending moment from the thermally induced force in those tubes offset from the vertical plane between the center-line of the two headers.*

Potential HRSG Damage: *Thermal fatigue, creep fatigue and corrosion fatigue.*

Restricted axial expansion of tubes (caused by any one of a number of mechanisms) induces forces and bending moments in the tubes. When straight tubes are attached to an inlet and outlet header at each end (Figure 7-1), restricted differential expansions will occur whenever some of those tubes are heated to a different temperature relative to other tubes attached to the same relatively-stiff headers. Tube temperatures closely and quickly follow the temperature of the fluid flowing through them and therefore anomalies in temperature and flow rate of the fluid between tubes in the same row can cause significant differences in the average temperatures of tubes attached to the same pair of headers. This can be a transient phenomenon during unit startups or shutdowns, or it may be a steady state condition on load. These conditions can exist in the HP superheater, reheater, evaporators, economizers, or preheaters.

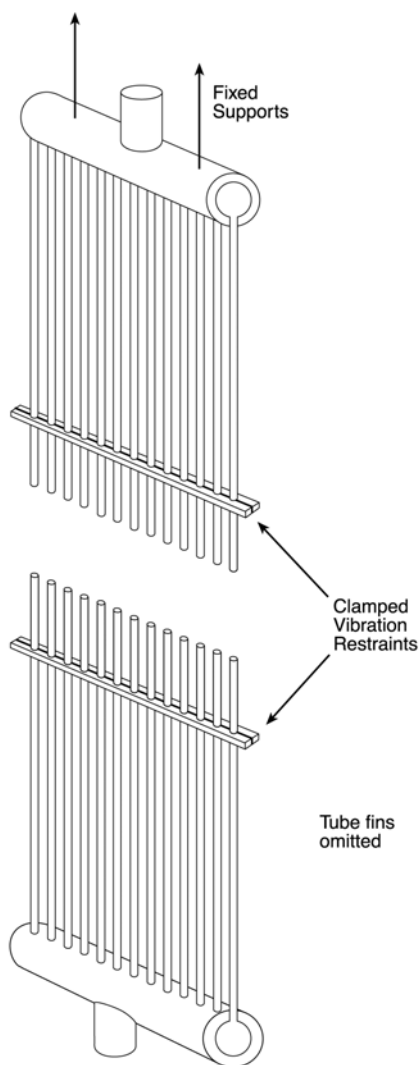


Figure 7-1
Illustration of the development of restricted axial expansion of tubes caused by attachment of straight tubes to an inlet and an outlet header.

The thermally induced forces in the tubes usually develop maximum stresses at tube attachments to the headers, or in small radius bends where these are used to connect tubes to one or both headers. The magnitude of the cyclic stress range is determined by a combination of peak average temperature differences between tubes, in conjunction with the extent to which the tube and header layout arrangements and the local tube-to-header attachment design enhance the bending component and local concentration of the thermally induced stresses.

When panels are assembled from two or more parallel-pass rows of tubes between the same upper and lower headers (Figure 7-2), the thermally induced forces developed by temperature differences between the majority of the tubes and one or more tubes that are connected to one or both headers by an acute bend develop both a direct force and a bending moment in the bend and at the attachment weld between bend and header. The bending moment substantially intensifies

the maximum thermally-induced stress at the attachment weld between tube and header, thereby considerably reducing its fatigue life.

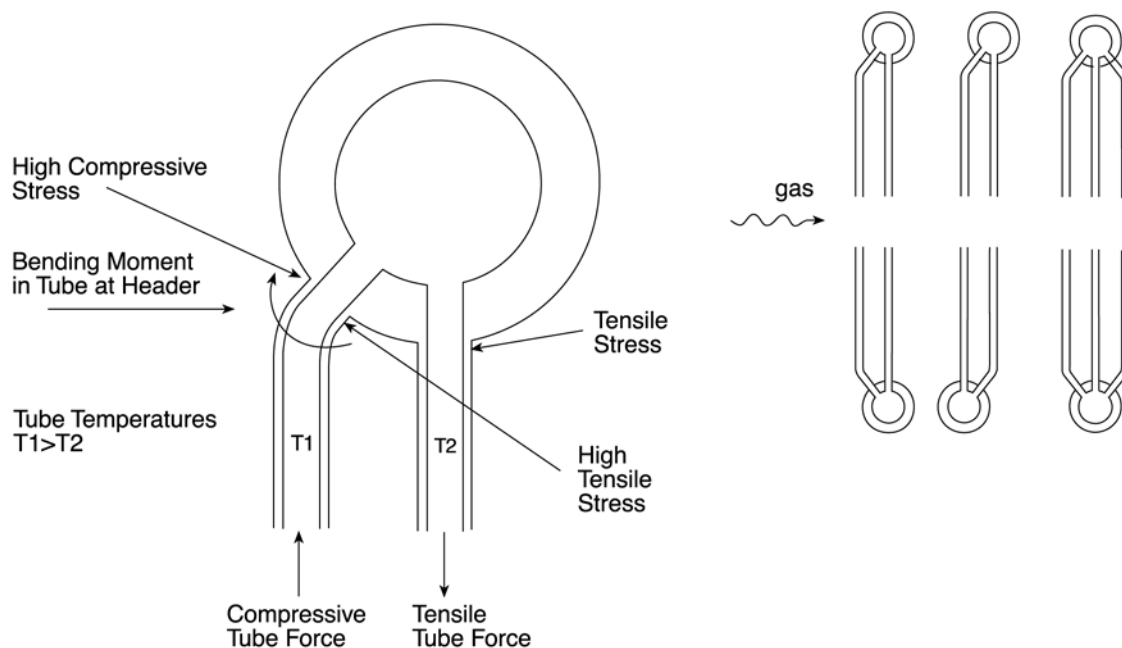


Figure 7-2
Differential expansion of tubes arranged with two (or more) passes with small radius return bends between passes.

Most very early service life thermal fatigue and corrosion fatigue failures in HP superheaters, reheaters and economizers have occurred not in straight tubes connected radially at the bottom or top of the headers, but at the attachment weld between an acute tube bend and header, or occasionally in small radius bends.

Several mechanisms can cause tube-to-tube temperature differences in tubes that notionally are presumed to operate at similar temperatures. As a result, there is a significantly higher probability of premature fatigue-related failures at attachment welds between tube bends and headers. Potential mechanisms include:

In HP superheaters and reheaters:

- The presence of undrained condensate in a few tubes during startups.
- Transient differences in tube temperatures between first and second rows of parallel pass tubes sharing the same upper and lower headers when uncooled during initial startup of the CT.
- Overspraying to saturation in HP superheater or reheater attemperators.
- Maldistribution of HP superheater or reheater attemperation water due to poor atomization and inadequate time for water to flash and mix.

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In preheaters and economizers:

- During startups in sequential multi-pass (e.g., “W” flow arrangement) type of economizers/preheaters that have two or three parallel-pass tube rows in each panel.
- In economizers that have shared upper and lower headers for different sections with internal pressure plates.
- Flow recirculation in economizers/preheaters.
- Maldistribution of feedwater.

The next sections evaluate various manners in which these stresses can develop.

7.6 Tube and Panel Differential Expansion in Horizontal Gas Path Designs

Action 7.6a *For HGP HRSGs, where possible, design panel supports to ensure that load transfer between different supports does not occur on heating or cooling caused by unit transients. If load transfer between supports will occur, perform additional calculations to confirm that an acceptable design life will result.*

Action 7.6b *Ensure that supports for horizontal tubes in VGP HRSGs allow for tubes to slide axially during expansion and contraction.*

Rationale: *Global temperature differences applied to tubes and interconnecting pipes between panels that are constrained from expansion result in high stresses.*

Potential HRSG Damage: *Creep fatigue, thermal fatigue or corrosion fatigue failures in the vicinity of tube attachment welds to headers.*

Large HRSGs of the horizontal gas path (HGP) type have many panels, (sometimes referred to as “harps” or “racks”), comprising one, two or three rows of straight vertical tubes welded either directly, or via small-radius, acute bends to the same pair of upper and lower headers.

This source of stress involves global temperature differences (i) between tubes within the same panel comprising one or more tube rows attached to the same pair of headers, or (ii) between panels of tubes in a module that share the same support system. Such stresses have been a major cause of early fatigue-related failures at tube attachment welds to headers or at adjacent tube bends in superheaters, reheaters and economizers of some HGP designs of HRSG.

The first effect, that of constraint of tubes by relatively stiff headers was discussed in general in Section 7.5. Some comments specific to HGP designs are included here and contrasted with similar considerations for VGP designs. The tubes and headers of all larger HRSGs of the horizontal gas path (HGP) type are top-supported from cold steelwork. The thermal expansion of the vertical tubes from cold to hot condition is accommodated by downward displacement of the lower headers. The header/tube arrangement is stiff in the plane of expansion and contraction of the tubes. In consequence, even a quite moderate and fleeting transient difference between the temperature of one or more tubes and the other tubes attached to the same pair of

headers will develop potentially damaging thermal stresses at the tube attachment welds to the headers. The largest tube temperature differences and associated axial tube forces usually occur during startup or shutdowns, or during attemperation in the HP superheater and reheater. These forces develop cyclic thermal-mechanical stresses that can cause (i) thermally-induced fatigue at the toe of tube-to-header attachment welds, or (ii) internal corrosion fatigue.

In a series of tests, ‘temporary’ thermocouples were attached to many tubes close to the upper and lower headers on several different designs of HGP HRSGs [7-3]. These tests established that temperature differences much larger than expected can occur between tubes attached to the same pair of inlet and outlet headers of superheaters, reheaters and economizers [7-3].

The second effect of temperature differences between tubes in HGP designs relates to supports. In most HGP designs, several panels (harps or racks) are joined into factory-assembled modules with interconnected pipes between upper or lower headers to convey the feedwater or steam from the outlet of each panel to the inlet of the subsequent heating panel. The modules and constituent panels are usually supported on fixed slings so that the gravity forces in tubes and supports are reasonably shared between all tubes when installed and cold. During load, the panels that operate with tubes at higher temperatures expand by greater amounts relative to the panels with cooler tubes. As a result, forces and moments are developed in the interconnecting pipework at its attachment to headers. Furthermore, in some designs of HGP HRSG the thermal expansion of tubes when hot causes substantial redistribution of gravity loads within the module, unloading some fixed supports and significantly increasing forces and bending moments in the more highly loaded tubes and supports.

For HGP HRSGs it is recommended that panel support arrangements ensure that load transfer between the different supports does not occur when the modules are heated from cold to hot operating conditions. For those designs of HGP HRSG that do, undesirably, cause redistribution of loads between different panels in a module when heated from a uniform module temperature, then the additional thermal-mechanical stresses in the tubes at bends and attachment welds should be calculated and the associated design life determined.

VGP HRSGs have predominantly horizontal tubes and the gas rises vertically through the heating surface sections. Inlet and outlet headers can be located on opposite sides of the vertical duct or one above the other on the same side of the HRSG. Provided that the supports for the horizontal tubes of VGP HRSGs permit the tubes to slide axially during expansion and contraction without generating significant axial friction forces in the tubes, then problems similar to those in HGP designs should not develop, Figure 7-3. This is because each is free to expand independently of the other serpentine tubes in the same section of the HRSG. Supporting the tubes and headers on bare tubes by spectacle plates better ensures low friction-induced expansion forces in the tubes, as shown in the upper sketch in Figure 7-3.

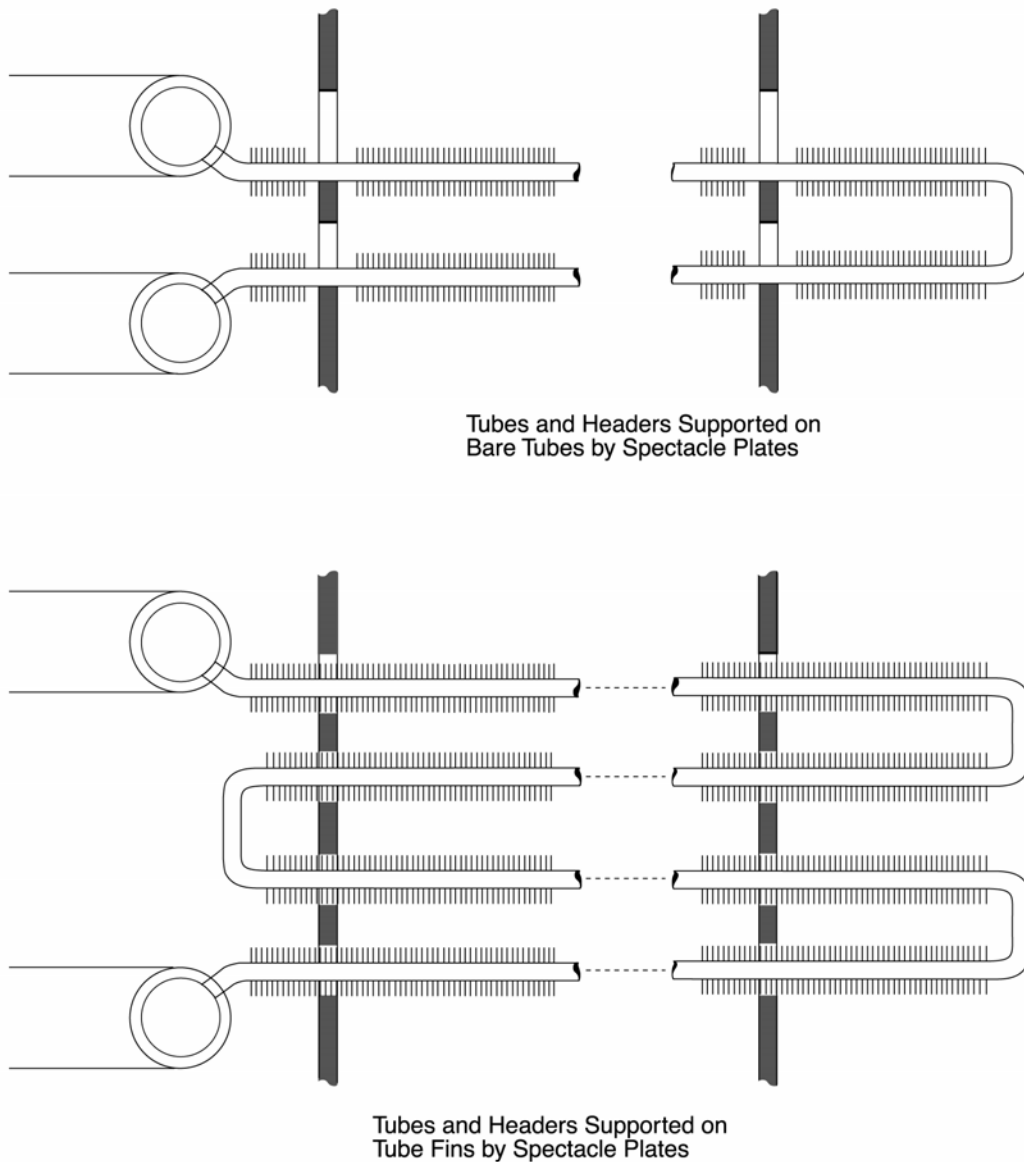


Figure 7-3
Tube and header support arrangements.

However, low cycle fatigue has been a major cause of tube failures in small VGP HRSGs of older design that used single passes of horizontal tubes between headers on opposite sides of the HRSG. These prevented differential expansions between tubes in the same row that transiently experienced significant tube-to-tube temperature differences during startups.

7.7 Thermal Transient Stresses on Startups in HP Superheaters and Reheaters – The Formation of Condensate and Inadequate Design and Improper Operation of the Drains

Action 7.7a *Ensure adequate superheater and reheater drain systems incorporating appropriate design features.*

Action 7.7b *Establish appropriate operating procedures for clearing condensate, particularly on unit startup.*

Rationale: *If condensate cannot be drained, the result will be high tube-to-tube temperature differences and thermal shock at tubeholes and the inner surface of SH/RH outlet headers.*

Potential HRSG Damage: *Thermal stresses in superheater and reheater tubes at their attachment weld to the header and at the inner surface of tubeholes, leading to thermal fatigue, corrosion fatigue or thermal quench-induced overload failures; water induction in the steam turbine.*

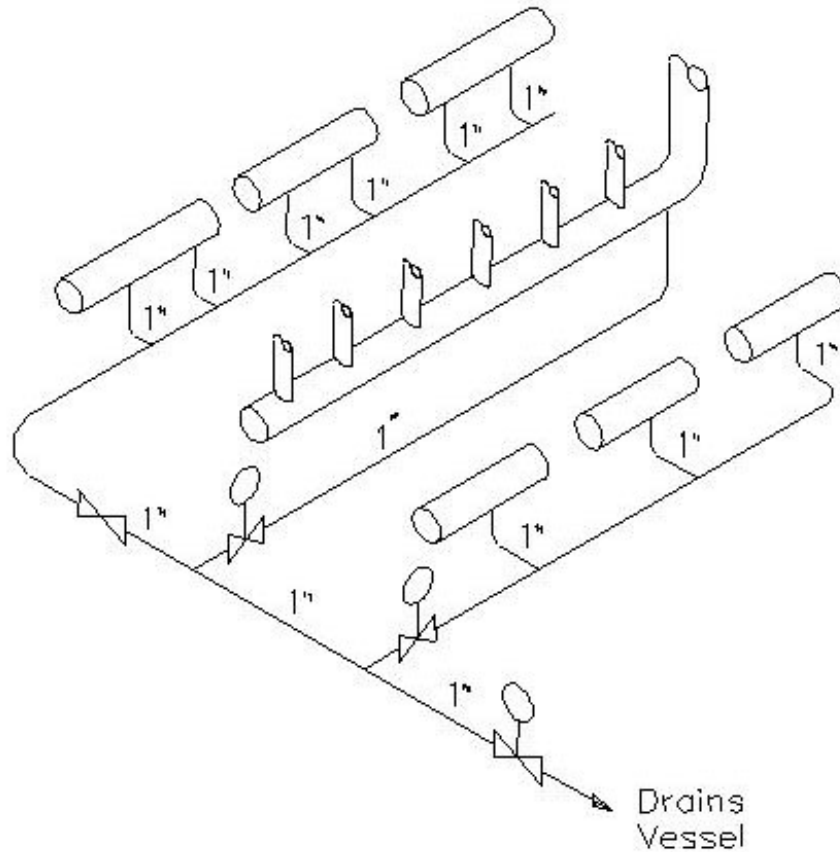
The most widespread cause of tube temperature anomalies in HP superheaters and reheaters is failure to completely remove all condensate from the lower sections of tubes, headers, steam pipes, manifolds, and attemperators before any steam flow is established through the HP superheater and reheater at each startup. Such condensate forms during CT shutdowns as well as during the CT purge.

Substantial quantities of condensate that cannot be completely drained from superheaters and reheaters can cause high tube-to-tube temperature differences and also thermal shock at the tubeholes and inner surface of superheater and reheater outlet headers. Superheater and reheater drains are not merely for maintenance as sometimes assumed. It is essential that they be utilized correctly during every CT startup and shutdown. Such condensate can also lead to water induction into the steam turbine.

To avoid these problems, it is preferable to design-in good drain system features. However, deficiencies in installed arrangements for drainage and disposal of condensate from superheaters and reheaters can usually be corrected by design modifications. Modifications are prudent for all HRSGs with deficient installed arrangements; they are essential for units expected to perform some periods of cycling operation. Elements of the design of drains removal and disposal systems to be included in initial designs or corrected in existing designs include:

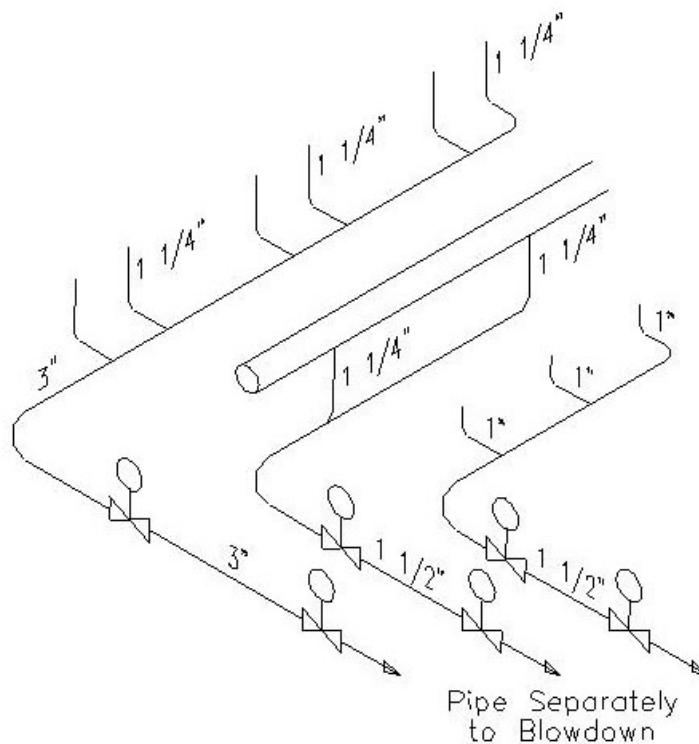
- Ensure that the lower headers of HP superheaters and reheaters have adequate diameter and sufficient number and size of drain connections to ensure that the condensate level in the headers remains at all times below all tubeholes.
- Drains from different sections of the superheater should not be interconnected into a single common drainpipe to the blowdown vessel (Figure 7-4). This is commonly done as it is the cheapest installation and the importance of reliable condensate drainage to the cyclic life of superheater and reheater components is not generally appreciated. Drains from different sections of a superheater (likewise for a reheater), which operate at any time at different pressures should never be interconnected. An example of a correct arrangement and sizing

for superheater drains is illustrated in Figure 7-5. The drains from each different section must be connected directly to a manifold on the blowdown vessel and have separate, duplicate, motor-operated isolation valves to ensure tight shutoff is maintained. This problem is illustrated in the case study that follows in Section 7.7.1.



Note: 1 inch = 2.54 cm

Figure 7-4
Incorrect interconnection of superheater drains to disposal [7-3].



Note: 1 inch = 2.54 cm

Figure 7-5

Correct drains disposal arrangement for superheater [7-3].

- Increase the drainpipe bore after each interconnection from locations always operated at the same pressure to maintain uniform mixed-phase fluid velocities along the pipe.
- Drain connections on lower headers and pipes, and valves to the blowdown vessel, must be generously sized to pass condensate at the maximum rate of formation.
- Drains are often undersized on the false assumption they pass only liquid. Condensate close to saturation temperature flashes after it enters the drainpipes and the pressure reduces. Pipes and isolation valves must be sized to pass the much higher specific volume of mixed phase flow.
- There should be a minimum of two drains on all lower headers of superheaters and reheaters that are notionally horizontal and located in reasonable proximity to the blind ends of the header to ensure that condensate can be completely removed when the header deviates from its intended horizontal position during cooling or heating of the panels. Additional intermediate drain points are recommended for longer headers to minimize the quantity of condensate that can pool along the bottom of the header.
- Where headers drain through interconnecting pipes into lower manifolds, these longer manifolds should be installed to have a positive fall to drain connections in the cold and hot expanded positions of the manifold to prevent pooling of condensate along the bottom of the manifold.

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- To protect the blowdown vessel from high pressure and temperature steam during hot starts, the drains should be collected in condensate pots equipped with level control switches that initiate automatic opening and closing of the drains. Allow adequate clearance beneath lower manifolds and the floor slab to accommodate condensate pots large enough to handle the maximum rate of condensation during purges (Figure 7-6).

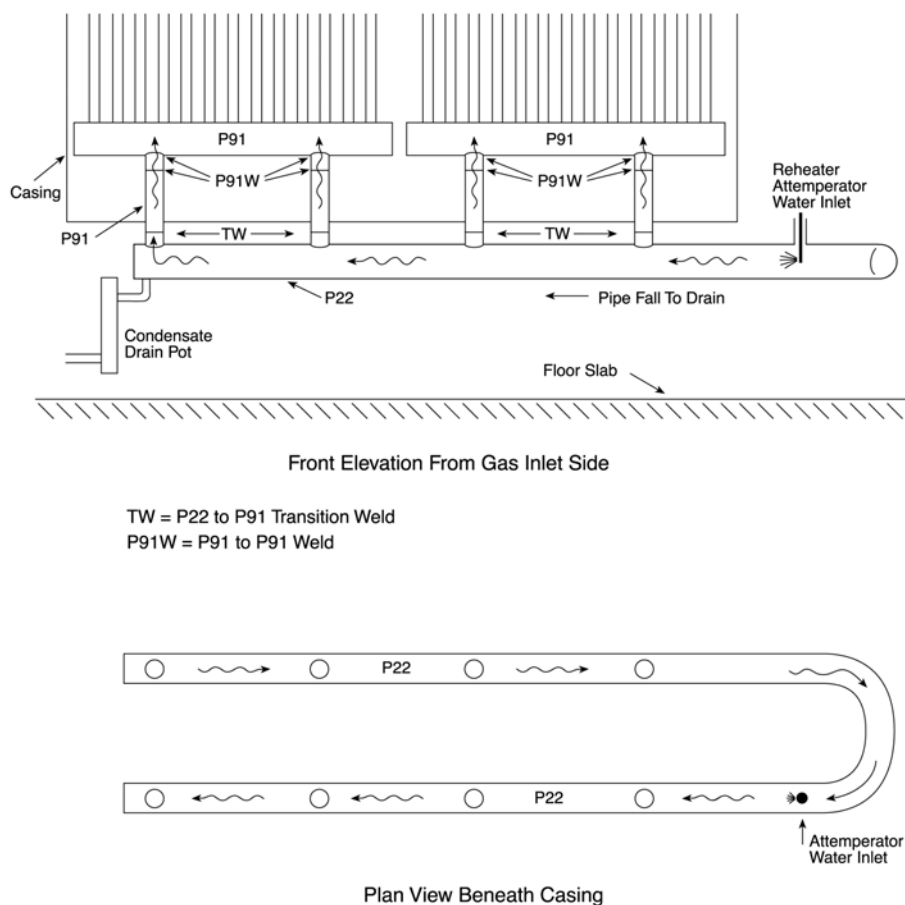


Figure 7-6
Drain and condensate pot arrangement.

- Most installations allow inadequate vertical space to accommodate drains. The elevation between all drain connections on lower headers, pipes and manifolds of superheater and reheat sections, and the inlet manifold on the blowdown vessel, must be sufficient to ensure adequate fall along the entire length of each drain pipe between drain point and blowdown vessel when the HRSG is hot and the drain connections on headers and pipes have expanded down to their lowest operating position (Figure 7-6).
- Operation of isolation valves on drain lines from superheaters and reheaters should be automated to ensure they are always opened when there is condensate in the drain pots and shut before the drain pot is completely empty to conserve superheater and reheat pressures and to protect the blowdown vessel from high flow rates of high temperature steam.

For HRSGs already installed with small bore headers, the following modifications are recommended to minimize the magnitude of transient tube-to-tube temperature differences caused by non-uniform draining rate between tubes in different positions along the headers:

- For HP superheater and reheater sections that have steam inlets and steam outlets at the upper headers, install small bore, orificed vents between the inlet and outlet pipes of each superheater and reheater section. This is intended to prevent condensate from being drawn up the downstream tubes from flooded lower headers during purges of a pressurized HRSG by the 'vacuum' relative to the HP drum pressure created in the downstream tubes by the condensation process. The condensate behavior in the superheater during purge is shown in Figure 7-7.

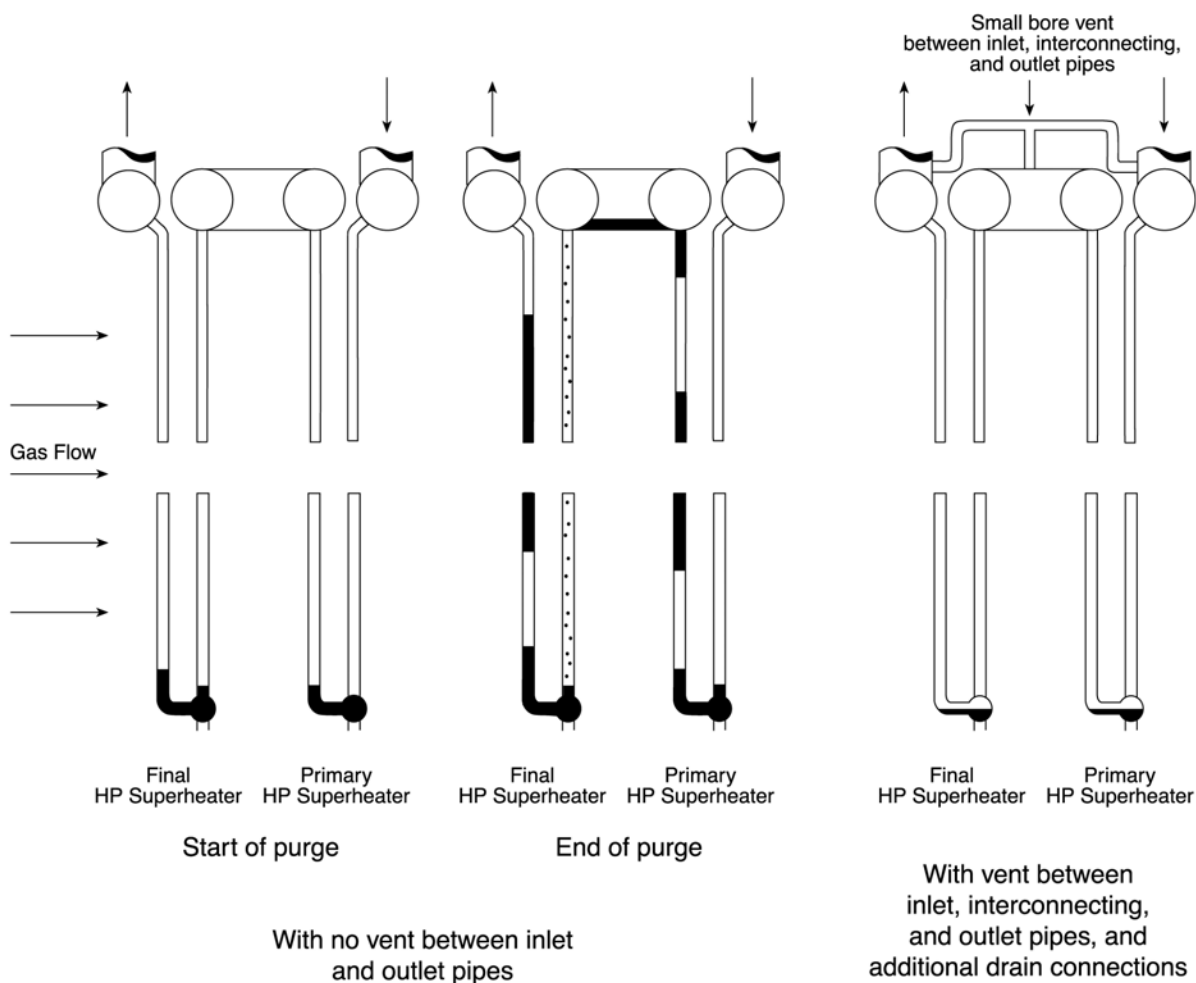


Figure 7-7

The condensate behavior in the superheater during purge [7-1].

- Install additional drain points on the lower headers, condensate pots with level switches, and larger drains disposal piping to blowdown to match the rate of removal of condensate to the maximum rate of formation of condensate.

Two case studies illustrate the importance of incorporating the design features described above.

7.7.1 Case Study on SH and RH Outlet Tube Differential Chilling by Condensate

Figure 7-8 shows the measured temperature versus time curve for several superheater tubes for a period of approximately one hour after a cold CT start. The superheater and reheater drains were opened long before the startup, and remained open. However, when a small flow of HP steam was established to warm the HP steam pipes, the consequential small pressure drop through the superheater caused condensate and saturated steam mixture to be displaced forward and upwards selectively through some tubes of the final steam outlet row of tubes.

The affected tubes were chilled at their outlet by up to 75°C (135°F) relative to other tubes, which continued to follow the rise in gas temperature. An example can be seen for Tube #5 in Figure 7-8. Even though the condensate or saturated steam had been heated during passage upwards to the thermocouple position at the top of the 20 m (65 ft.) long tube, it remained at saturation temperature at the tube outlet for about 15 minutes.

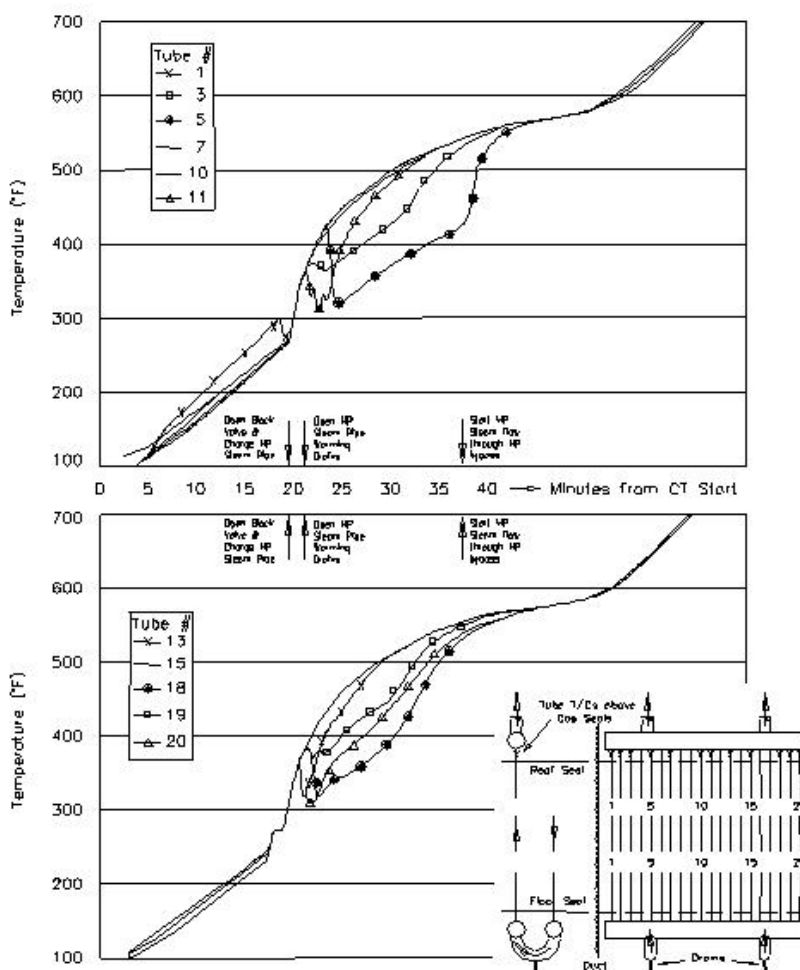


Figure 7-8
Superheater outlet tube row arrangement and tube outlet temperature during cold start [7-3].

Although this HRSG was nominally provided with drains at all low points of superheaters, and the blowdown vessel was installed in a pit to facilitate continuous drain pipe fall to the vessel, a substantial quantity of condensate could not be removed, and was finally cleared into the hotter outlet pipe and header when the HP bypass valve opened and established a larger steam flow. A similar phenomenon was measured on tubes of all earlier sections of the superheater.

During the same typical cold start, a similar phenomenon occurred in all sections of the reheater, which were also expected to have completely drained prior to startup. The steam outlet section of the reheater was comprised of two staggered rows of upflow tubes with both rows attached to the same upper and lower headers. Each tube was offset from one of the headers, which significantly intensified the maximum thermal stresses caused by tube-to-tube temperature differences.

Figure 7-9 highlights how during the initial part of the startup, when conditions inside the reheater were stagnant, the uncooled row A tubes, which are exposed to inlet gas flow, heated up quicker than the row B tubes. Some reheater row A tubes were up to 56°C (100°F) hotter than adjacent row B tubes. This temperature difference may be large enough to cause localized inelastic stresses, thus creep-fatigue damage, at the weld of offset tubes to the header. Even more disturbing, when forward flow was established through the reheater during pressurization from HP bypass steam flow to the cold reheat pipe, undrained condensate remaining in lower sections of the reheater was displaced forward and blown up selectively through some of the row A tubes.

For example, Tube #A18 was chilled at its outlet to as much as 167°C (300°F) below most of the nearby tubes. This resulted in severe inelastic stresses occurring at the weld of this offset tube to the upper outlet header that are likely to initiate creep-fatigue cracks in the weld after a small number of similar cycles. Some other row A tubes were also chilled at the outlet by condensate or saturated steam. More condensate was displaced forward for several minutes through a few tubes after hot reheat steam flow was initiated. The phenomenon was never observed in any row B tubes, which at inlet are offset towards the side of the header. It tended to be more prevalent on row A tubes with inlets positioned in proximity and opposite one of the header inlet pipe branches, and in tubes near to one or other blind end of the header. This pattern suggested that the headers tilt from horizontal during the shutdown and startup. Similar behavior was observed at tubes in earlier stages of the reheater.

Much of the damaging condensate blown out of the final superheater tubes in Figure 7-8 came from earlier, separately drained sections of the superheater through the superheater drain pipes which had been interconnected into a single small bore pipe. That pipe was supposed to drain all condensate to the blowdown vessel, as illustrated in Figure 7-4. As a result of interconnecting, in this example, ten nominally 2.5 cm (1 in.) diameter drainpipes were taken from three different superheater sections into a single 2.5 cm (1 in.) diameter longer pipe of identical flow area. When the steam flow, and thus pressure drop, was established through the superheater, the path of least resistance for condensate from the higher pressure sections of the superheater was through the six 2.5 cm (1 in.) drain connections intended to remove condensate from the final section of the superheater, rather than through the single 2.5 cm (1 in.) pipe to the blowdown vessel.

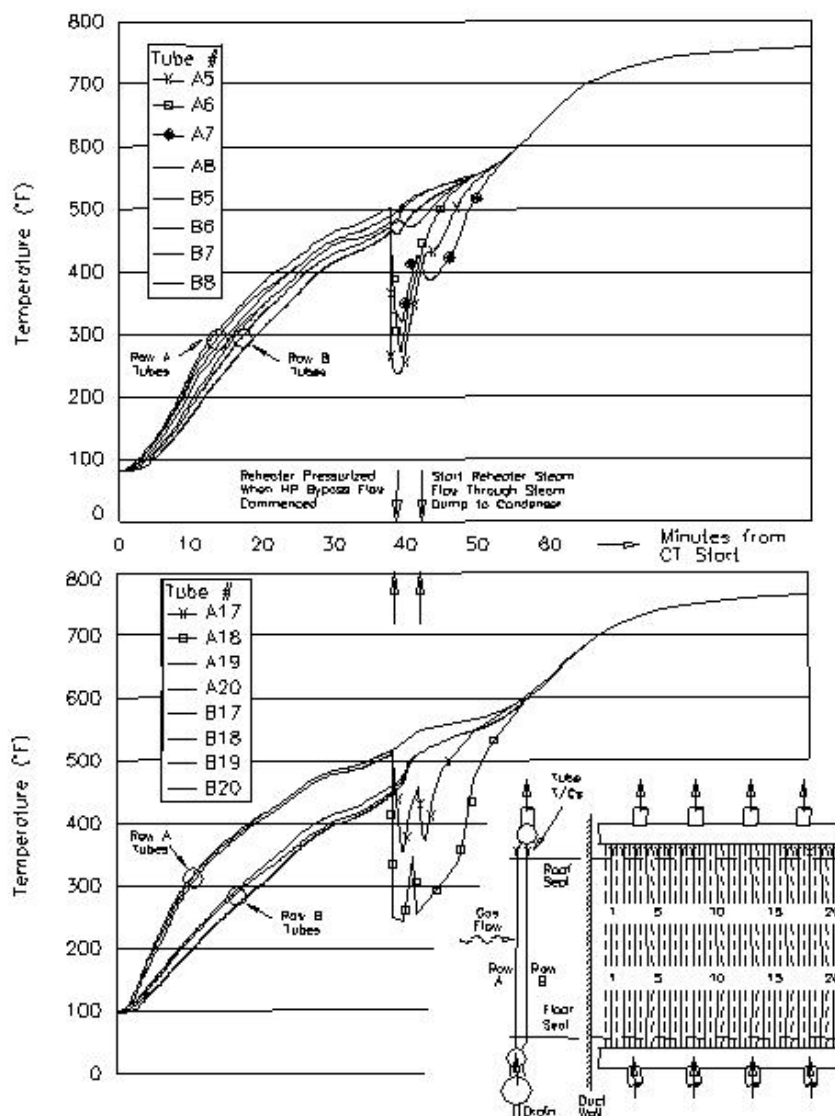


Figure 7-9
Reheater outlet tube rows arrangement and tube outlet temperature during cold start [7-3].

7.7.2 Case Study – Selective Chilling in Another HRSG Design

The phenomenon of selective chilling of some tubes by condensate immediately after establishing forward flow and pressure gradient through the HP superheater has been observed during tube temperature measurements on several different designs of horizontal gas path HRSGs during cold, warm and hot starts.

Tube temperatures recorded during a typical hot start on a large, non-reheat HRSG are illustrated in Figures 7-10 and 7-11. The final outlet section of this superheater has three rows of tubes with 18 tubes in each row, arranged in-line parallel to the direction of gas flow, Figure 7-10. Row B tubes are perfectly straight and connected at bottom- and top-dead centers of upper and lower headers, respectively. Row A and row C tubes are each offset and connected by small

radius bends to upper and lower headers, which intensifies the maximum thermal stress developed by any thermally-induced forces in these tubes.

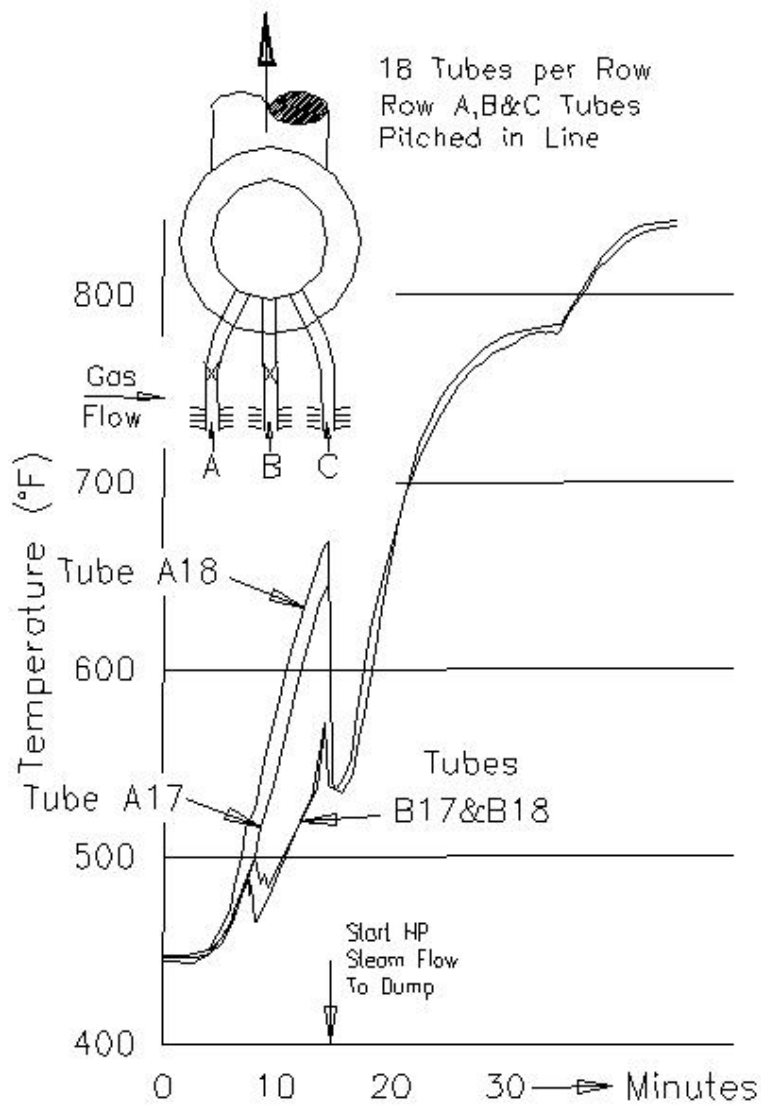
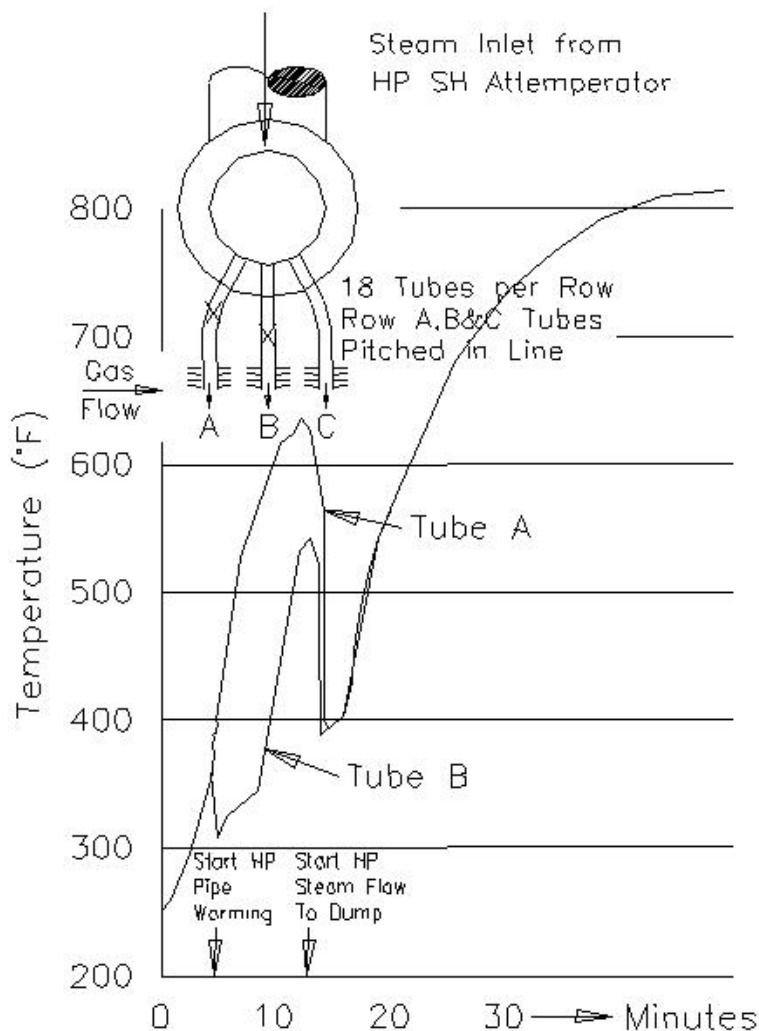


Figure 7-10
Tube temperatures at outlet from final HP SH panel – hot start [7-3].

**Figure 7-11****Tube temperatures at inlet to second stage HP SH – cool start [7-3].**

Prior to establishing any flow in the superheater, row A tubes, which are most directly exposed to the inlet gas flow, were heated up to 67°C (120°F) above the row B tubes. At the steam inlet to the second stage HP superheater, positioned in the steam path after the desuperheater, the row A tubes of this panel were heated more than 111°C (200°F) above the row B tubes, Figure 7-11, and developed high thermally induced stresses at the attachment of the offset row A tubes to the headers. When steam flow was initiated, a substantial quantity of condensate was blown forward through many tubes in all sections of the superheater, Figures 7-10 and 7-11, chilling tubes and quench cooling the tube holes through the outlet header wall. This HRSG was installed without any means for removing condensate when the unit is warm or hot.

7.8 Row-to-Row Tube Temperature Differences in HP Superheaters and Reheaters during Startups

Action 7.8a: *Utilize single row panels in HP superheaters and reheaters.*

Action 7.8b: *For designs that use panels with more than one row of tubes, perform analysis to verify that the thermal stresses developed by the peak temperature differences between the tube rows during startups and shutdowns are compatible with the design creep fatigue life. The analysis of transient row-to-row tube temperature differences must incorporate the simultaneous stresses developed at tube-to-header welds by the tube-to-bulk-header temperature difference during startups.*

Rationale: *Peak row-to-row and tube-to-header temperature differences in HP superheaters and reheaters during cold, warm and hot startups, normal shutdowns and trips must be quantified in order to verify the compatibility of the HRSG design with the target cyclic life.*

Potential HRSG damage: *Creep fatigue at tube attachments to headers.*

During the initial part of CT startups, until the CT is synchronized and established on minimum spinning reserve load, there is little or no cooling steam flow through HP superheater or reheater. The inlet row of tubes lag a few minutes behind the gas temperature due to the thermal inertia of the tube wall fins (Figure 7-12(b)). Since the gas temperature drops as it gives up heat to each successive row of uncooled tubes, the subsequent rows of tubes heat up at a progressively slower rate. For panels comprising more than one row of tubes, a transient temperature difference develops between the first and second row (relative to the gas flow) of each panel (Figures 7-12(a) & 7-12(c)).

Where panels comprise single rows of tubes per pair of upper and lower headers, and the peak temperature differences between rows interconnected by jumper pipes have been conservatively established, the analysis to determine stresses imposed on tube and pipe connections to each header is relatively straightforward. However, in the example in Figure 7-12, the panels have two rows of tubes in each panel that develop significant row-to-row temperature differences during CT startups. The thermal stresses in the tubes caused by the peak row-to-row temperature differences will be higher and a more complex elastic analytical model must be used to determine the thermally-induced stresses. In the illustration given in Figure 7-12(a), analysis should be done of the entire secondary superheater, comprising:

- The HP4 panel, here with a peak tube-to-tube temperature difference of about 52°C (94°F) (Figure 7-12(c)).
- The HP3 panel with a tube-to-tube peak temperature difference of about 24°C (43°F).
- The interconnecting pipes here with a peak panel-to-panel-average tube temperature difference between the HP4 to HP3 panels of about 200°C (360°F).

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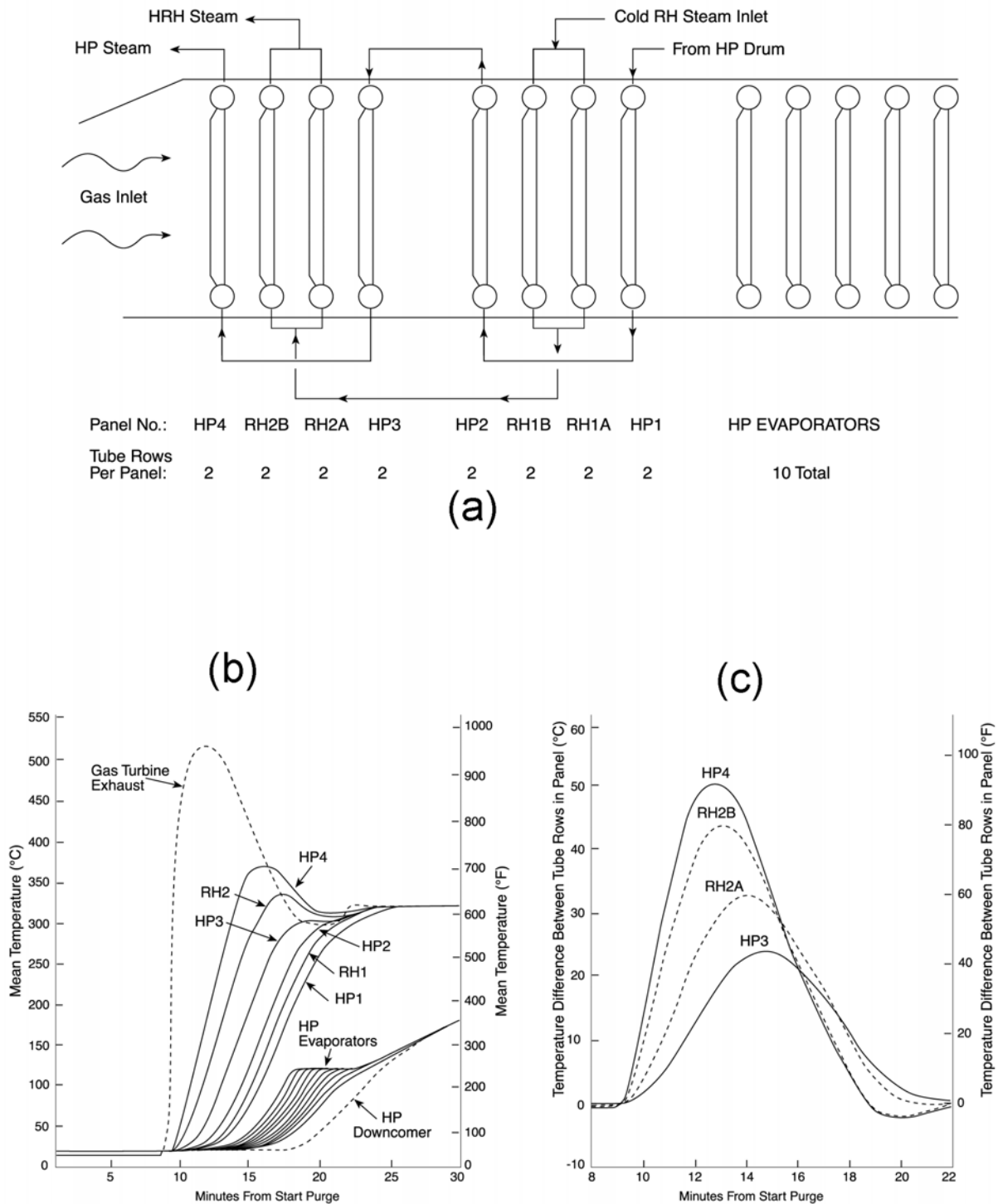


Figure 7-12
Startup thermal transient effects on tube row temperatures.

The stress analysis model should include the entire tube panel, supports and piping forces, moments or displacements.

Some HRSG OEMs calculate the transient temperatures in every row of HP superheaters and reheaters as part of their standard design verification process. This is done by dynamic simulation of the response of the HRSG HP evaporator and HP superheater and reheater sections to the gas temperature and flow rates as a function of time during startups. The results from the dynamic simulation are essential boundary conditions for finite element determination of the peak stresses at the outer surfaces of key components.

7.9 Performance of HP Superheater and Reheater Attemperators

Action 7.9a: *Ensure attemperators are positioned between primary and secondary superheaters/reheaters so that there are no conditions when overspraying too close to the saturation temperature can occur.*

Action 7.9b: *Ensure adequate straight lengths are provided upstream and downstream of attemperators to ensure complete mixing and flashing of all spray water before the first downstream pipe branch.*

Action 7.9c: *Ensure that leakage of water past spray control valves cannot enter headers and quench tubes and headers, by the appropriate layout of pipes and attemperator, pipe drains and controls for spray water isolation valves.*

Rationale: *The admission of unmixed or unflashed attemperation water into downstream superheater/reheater headers causes the water to be concentrated in those tubes opposite the header inlet pipe nozzle, and to develop significant tube- to- tube temperature differences. Quench cooling of hot tubes can cause thermal fatigue or in some instances ductile overload failures in tubes.*

Potential HRSG Damage: *Overheating of some tubes and creep fatigue or thermal fatigue or corrosion fatigue at tube attachments to the upper and lower headers; ductile overload tube failures.*

7.9.1 Division of Heating Surface Before and After Attemperators

Large dry low NO_x combustion turbines maintain or increase exhaust gas temperature when output is reduced. Overspraying too close to saturation, or in some installations right down to saturation, occurs at part load when combustion turbine exhaust gas temperature is at its maximum unless the attemperators are properly located. Overspraying in HP superheater or reheater attemperators can create thermal stresses in pipe branches, headers and at tube attachment welds to headers caused by localized concentrations of unflashed spray water and variations in steam temperature.

During the conceptual design stage, a range of heat balance calculations should be run to verify that there is always a minimum of about 47°C (86°F) superheat at the attemperator outlet. This should be done for all operating conditions.

During more rapid pressure raising in the HP drum, steam flow rate through the HP superheater falls significantly because most of the evaporation is utilized for pressure raising in the vapor space. The ability of the HP superheater attemperators to limit the HP steam temperature to the design limit without overspraying to saturation temperature during rapid pressure raising should be verified. This can be accomplished by dynamic simulation of the HP conditions in the HRSG and verifying that attemperation can be achieved without overspraying.

7.9.2 Space for an Efficient Atomization of Attemperator Spray Water

An adequate straight length of pipework from the discharge of the attemperator is required to permit the completion of flashing of water droplets and the mixing of the desuperheated steam before the steam reaches the first pipe branch that distributes the steam into the headers.

Where attemperators have been installed immediately before or after a pipe bend (Figure 7-6), with short distance to the first pipe branch, very large temperature discrepancies have been measured at inlet to the downstream tubes. Tube temperature at outlet from those tubes differ by up to 55°C (100°F) with hotter tubes up to 28°C (50°F) above their design limit temperature.

7.9.3 Prevention of Quenching of Hot Tubes by Improper Admittance of Attemperation Water

There have been several tube failure incidents in HP superheaters and reheaters caused by the improper admission of attemperation water into the superheaters or reheater tubes when there was no or low steam flow. The cool water quenched those tubes closest to the inlet or outlet pipe branch on the headers either upstream or downstream of the attemperators and in some cases developed thermally-induced tensile forces in the quenched tubes large enough to cause ductile overload failures. There have been various root causes of this problem. These have included:

- Misuse of attemperators to force cool the HRSG
- Failure to repair defective spray water block valves or their actuator
- Too slow closing time on block valves
- Lack of or inadequate control automation to ensure that the block valve is shut whenever desuperheating is not required
- Failure to repair excessive leakage past control valves
- Poor performance by attemperator controls
- Poor pipe arrangements to and from the attemperators that allowed leaking water to run quickly into headers and tubes.

In order to minimize the risk of similar events in future the following actions are recommended:

- Automate the opening and closing of the spray water block valve so that it is only open when CT exhaust gas temperature exceeds the design control HP or reheat steam temperature, respectively, and shut automatically whenever CT exhaust gas temperature is below the block valve open setpoint.
- If practical, locate the HP superheater and reheater attemperators either between a top outlet header (before the attemperator) and a bottom inlet header (after the attemperator) or between a bottom outlet header (before the attemperator) and another bottom inlet header (after the attemperator).
- Drains, sized to remove significant leakage past the control valve when there is little pressure in the pipe, should be routed to condensate pots with level switches for automatic operation of attemperator pipe drain valves.
- Ensure that adequate clearance is provided beneath the HRSG casing for interconnecting pipes and attemperators, downward expansion of tubes at maximum temperature, adequately sized condensate pots, pipe falls to condensate pots, and gravity drain of pipes from condensate pots to the blowdown vessel.
- Attemperators in inlet or outlet pipes connected to top headers are not recommended because any water spuriously admitted may flow towards a hot header under low flow conditions. Where top attemperators are unavoidable, arrange piping to have low points between attemperator and both upstream and downstream headers installed with condensate pots and level switches arranged for automatic operation of drain isolation valves.
- Install air-operated attemperator spray water block valves for fast shutoff.
- Ensure that any malfunction of the block valve is noted and repaired at the next outage.
- Regular maintenance of the attemperator spray water control valves should be performed to ensure minimum leakage when they are shut.

7.10 Evaporators

Action 7.10: *Verify by analysis and measurement that evaporator downcomer, interconnecting pipes, headers, tubes and risers have flexibility compatible with the cyclic design life.*

Rationale: *Evaporator circuits develop significant transient temperature differences between successive tube rows and downcomers during startups.*

Potential HRSG Damage: *Thermal fatigue in tubes, pipes and downcomers.*

There have been a few cases of thermal fatigue failure in downcomers, interconnecting pipes or risers in HP and LP evaporators. There is a perception that evaporator circuits always operate at a closely similar temperature to the downcomers, pipes and tubes. However, this is not the case during startups from cold, warm, or hot initial conditions.

During starts, especially from low drum pressure conditions and prior to the commencement of evaporation in the tubes, the tubes, fins and water contents heat up at different rates as the gas temperature drops progressively through the evaporator tube rows as less heat is transferred to each successive row (Figure 7-13). In some startup cases, particularly where the risers from the different rows of evaporator tubes are interconnected before the piping to the drum, the rear row tubes may short-circuit the downcomers, which increases the peak transient temperature difference between the gas inlet row evaporator tubes and the rear row tubes and downcomers.

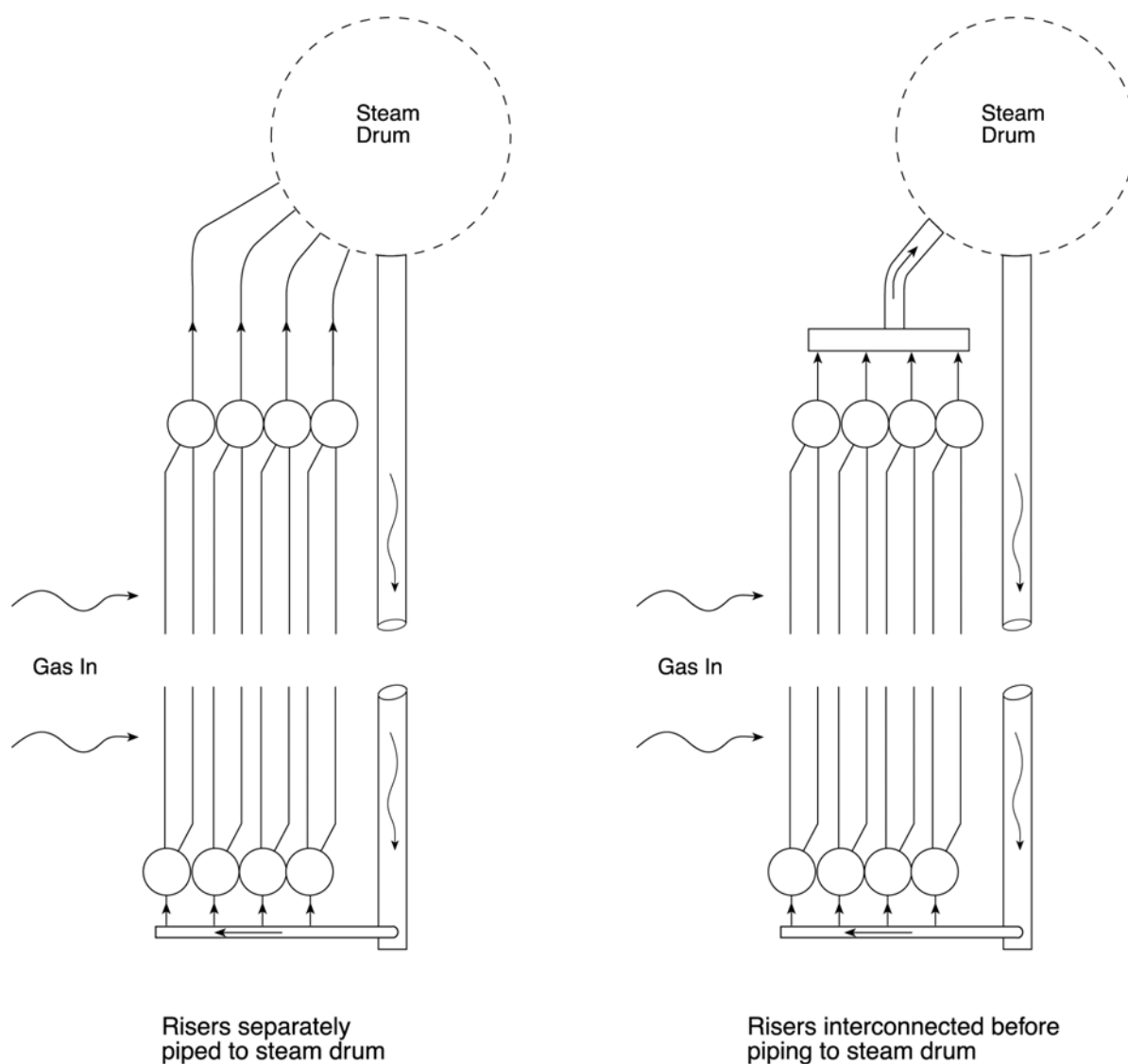


Figure 7-13
Evaporator tube arrangements with separate and interconnected piping to the steam drum.

During cold starts from ambient conditions, the temperature difference in HP evaporators between tube rows varies approximately linearly from front to rear row. The peak temperature difference between front row tubes and the downcomer can be up to 100°C (212°F) (Figure 7-12(b)) depending on the initial temperature of the evaporator circuit. This transient temperature gradient will lead to differential thermal expansion of the tubes, risers and downcomers, which may produce high forces and moments and reduce the cyclic life of selected weld connections or fittings.

During hot and warm starts, the evaporator tubes are initially close to the saturation temperature and evaporation commences earlier in the startup, and the peak temperature difference between front and rear row tubes is somewhat smaller. However, on HRSGs which locate the downcomers outside the gas path, significant subcooling can occur in the downcomers during the shutdown period and it is prudent to assume similar peak temperature differences between front row tubes and the downcomers for the design total lifetime number of startups.

HP, IP and LP evaporators are all susceptible to significant transient temperature differences between tubes and downcomers during startups and it is recommended that a thermal-mechanical stress and cyclic life analysis of the entire evaporator circuit be performed.

Temperatures at top of gas inlet row and gas outlet row tubes and downcomers should be measured during cold, warm and hot starts during commissioning to verify the assumptions made for design life calculations (see Section 10-3).

7.11 Venting, Steaming and Support Issues in Economizers

7.11.1 Venting to Avoid Steaming in Economizers - Overview and Key Design Aspects

Action 7.11a: *Economizers should be designed to ensure that all air and any vapor that forms during startups, or load reductions is immediately removed upwards by gravity and vented.*

Action 7.11b: *Purchasers should request that venting of economizer high points be included in the design or other equivalent means to ensure that large transient thermal stresses are not developed as a result of steaming the economizer.*

Rationale: *Tube temperature anomalies in economizers caused by deficient venting arrangements are a source of significant thermal stresses and fatigue, and also create a potentially corrosive environment inside the tubes.*

Potential HRSG Damage: *Thermal fatigue in bends and at tube-to-header connections; increased deposition and corrosion mechanisms in economizer tubes; increased potential for flow-accelerated corrosion.*

Many HRSGs have economizers arranged with sets of parallel flow vertical tubes up to 21 m (69 ft) high through which feedwater is intended to flow uniformly up and then down, or down and

then up, through a series of many tube rows. Extensive steaming occurs in all sections of economizers during startup and loading of the combustion turbine/HRSG unit, and also when drum pressures fall while on load following upset conditions on the combined cycle unit. Steaming occurs while economizer flows are stagnant until drum swell subsides. The vapor that collects at unvented highpoints is also difficult, in some cases impossible, to remove from every tube. As a result, in some designs of HRSG, some tubes in each parallel pass may never clear and are continuously vapor locked, even at stable high load.

Economizer designs which attach all tubes to the upper and lower headers should be installed with a vent from every high point on each upper header or jumper pipe between headers.

The consequences of air- or vapor-locking and flow stagnation or reversal in tubes of hairpin-type economizers and preheaters raises several concerns regarding their impact on the durability of the economizers and preheaters, especially for HRSGs intended for cycling service. These include:

- Potentially significant thermally induced stresses in inlet and outlet row tubes at tube attachments to upper and lower headers, which can accumulate many cycles per startup.
- Potentially significant thermal stresses in the upper bend and at header attachments of hairpin tubes caused by intermittent chilling of tube inlet legs each time flow re-establishes.
- Fluctuating transfer of gravity loads between tubes as hotter tubes expand upwards and unload at the upper support bars.
- Unstable feedwater control influenced by fluctuations in system resistance as some tubes intermittently clear and then re-stagnate.
- Increased risk of flow-accelerated corrosion at tube bends, which intermittently vapor lock and then re-establish flow.
- Deposition of dosing chemicals on tube surfaces during steaming leading to obstruction of flow.
- Potential corrosive environment in tubes in proximity to the boundary between water and steam phases.

A common misconception is that steaming is only a short term problem during startups in the final row of economizer/preheater tubes, which are arranged to flow upwards and vent up to the steam drum. Since many units with unvented economizers have apparently operated without detectable problems, there appears to have been assumptions that (i) unvented economizer tubes do successfully blow out all air and vapor collected in high points during every startup, (ii) there are then no obstructions by air or vapor pockets in the economizers during normal operation, or (iii) that the presence of some air-locked or vapor-locked tubes have no impact on the durability of economizer tubes.

Tube temperature measurements on large HGP HRSGs have highlighted the presence of unvented high points in the economizers. This can (i) cause obstructions by air or vapor pockets, (ii) disrupt the intended distribution of feedwater through parallel-path tube circuits, (iii) develop potentially harmful thermally-induced stresses, and (iv) develop an adverse chemical environment in the critically affected parts of economizer tubes.

The practice of not providing vents at all high points developed from small HRSGs, which had much shorter tubes. For recent HRSG designs, it has become the standard practice of some OEMs, who traditionally supply economizers with all tubes connected to an upper and lower header, to provide operational vents from every high point on upper headers and interconnecting pipes in all economizers. Other existing HRSGs have additional operational vents from upper headers preceding the outlet header of each economizer section.

For new construction without high point vents in economizers, it is recommended that investigations, tests and/or analysis be performed to verify that all high points completely clear, or quantify the significance of measured tube temperature anomalies and other adverse consequences of air or vapor pockets on the cyclic life of economizer tubes.

7.11.2 Other Measures to Minimize Steaming in Economizers and Preheaters

There are a number of additional design practices that can minimize the potential for economizer steaming as described in this section. These include:

- Positioning of LP and IP feedwater control valves
- Positioning of IP and LP superheaters in the HRSG gas path
- Arranging combined cycle unit controls to prevent rapid changes in pressures in steam drums
- Minimization of gas leakage

Action 7.11c Locate the LP and IP feedwater control valves between the outlet of the respective preheater/economizer and steam drum, and design feedwater pumps and preheater/LP and IP economizers to operate at a pressure significantly higher than their respective drum operating pressures.

Rationale: Elevates the saturation temperature in the economizer tubes, thereby reducing the extent of steaming the preheater and economizers.

Potential HRSG Damage: Thermal fatigue in bends and at tube-to-header connections; increased deposition and corrosion mechanisms in economizer tubes; increased flow-accelerated corrosion.

Elevating the operating pressures of preheater/LP economizer and also the IP economizer by throttling across the feedwater control valves increases the saturation temperature of the feedwater in the tubes. As a result, there is lower risk of periods when the gas temperature at the inlet to the respective economizer/preheater section exceeds the saturation temperature in the tubes.

It is impractical to adopt a similar arrangement for the HP feedwater system and the final HP economizer. This is because at its higher operating pressures, the rate of increase in saturation temperature with increasing operating pressure is so low that it is impractical to elevate the pressure in the HP economizer high enough to obtain sufficient margin between the saturation

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temperature of the feedwater in the final HP economizer and the gas inlet temperature, which typically exceeds the saturation temperature in the HP drum by 8 to 14°C (15 to 25°F).

Action 7.11d *Locate the IP superheater section between the HP evaporator and the final HP economizer sections, and the LP superheater between the IP evaporator and the IP economizer sections of the HRSG.*

Rationale: *The small IP and LP superheater sections lower the gas temperature entering the downstream economizer sections, which minimizes the risk of steaming the economizers.*

Potential HRSG Damage: *Thermal fatigue in bends and at tube-to-header connections; increased deposition and corrosion mechanisms in economizer tubes; increased flow-accelerated corrosion.*

The heat removed from the gas by the IP and LP superheaters reduces the gas temperature by approximately 5 to 6°C (9 to 11°F) at the inlet to the HP economizer and IP economizer, respectively. This, as a result, reduces the susceptibility of the HP and IP economizers to steam under steady state operation, or during upset conditions in the HRSG following rapid load reduction or trip of one of two or more CTs on a two-on-one combined cycle unit.

Action 7.11e. *Design combined cycle controls to maintain stable pressures in HP, IP or LP steam drums, even during major upset incidents.*

Rationale: *Minimizes the risk of steaming the preheater and economizers.*

Potential HRSG Damage: *Thermal fatigue in bends and at tube-to-header connections; increased deposition and corrosion mechanisms in economizer tubes; increased flow-accelerated corrosion.*

When on load, most combined cycle units normally operate with the steam turbine in sliding pressure control, i.e., with HP and IP steam turbine inlet control valves 100% open. In sliding pressure control, HP and hot reheat steam pressures are proportional to the volumetric flow at the inlet to the HP and IP steam turbines, respectively. As the CT output is varied at normal control rates, the HP and hot reheat steam flows also change. Steam pressure also varies, but at a much slower rate due to the high thermal inertia in the evaporator sections. Under normal operation during controlled adjustment of the output from CTs, the HP and reheater pressures change relatively slowly and the difference between feedwater outlet temperature and saturation temperature in the HP and IP economizers remains reasonably constant.

However, a rapid large reduction in drum pressure causes the immediate reduction in saturation temperature of the feedwater in those economizer/preheater sections that do not have their feedwater control valve between the economizer/preheater and their respective steam drum. This causes higher temperature sections of those components to immediately flash to steam, thereby obstructing flow and causing unstable feedwater flow control.

Combined cycle units that supply a single steam turbine from two or more CT/HRSG blocks are particularly vulnerable to major upset incidents when one of the other CT/HRSG blocks trips, resulting in a large, rapid reduction in HP and hot reheat steam flows.

Large, rapid changes in HP and hot reheat steam pressures following major upsets can be avoided. This can be accomplished by arranging for the steam turbine controls to be capable of either sliding pressure control or inlet pressure control for both the HP and IP steam turbine inlet control valves. Then arrangements have to be made for the control mode to automatically switch from sliding pressure control to inlet pressure control if the HP or hot reheat pressure changes at a rapid rate. When conditions have stabilized after an incident, then the steam turbine can be returned to sliding pressure control by slowly opening the HP and IP steam turbine inlet valves such that HP and reheat pressure slowly reduce.

Alternatively, the IP and LP steam drums can be insulated from rapid changes in pressure by installing a drum pressure-sustaining valve in their outlet steam pipe, which can be arranged to limit the rate of change in steam drum pressure.

Action 7.11f Ensure that effective baffles are provided between tubes and duct side walls and between adjacent tube modules.

Rationale: Minimizes the risk of steaming the preheater and economizers by minimizing leakage past modules and to ensure that hotter gas exiting each module is mixed with the cooler gas exiting the final tube row of each module.

Potential HRSG Damage: Thermal fatigue in bends and at tube-to-header connections; increased deposition and corrosion mechanisms in economizer tubes; increased flow-accelerated corrosion.

Gas leakage along the duct wall gives up less heat to the tube on one side than the gas flowing between pairs of tubes. End tubes of rows downstream exposed to the less-cooled gas pick up more heat than other tubes in the same row which increases their susceptibility to steaming in hairpin tubed preheaters and economizers and contributes to flow recirculation in some designs of HRSG that use multipass panels (harps, or racks). Inadequate gas baffle arrangements have been reported to also cause dry out in end tubes of evaporators in some designs of vertical gas path type of HRSG [7-4].

As a minimum, effective gas baffles should be installed to minimize gas leakage between the gas inlet row end tubes of each module and the duct side wall and adjacent modules. Gas baffles should also be installed downstream of the gas outlet row of each module to ensure that the less-cooled gas leaking between end tubes and the duct side wall, or between end tubes of adjacent modules, mixes with the cooler gas exiting the last row tubes of each module, so that the gas leaking past the end tubes on the downstream modules has been fully tempered.

7.11.3 Support and Load Redistribution in Hairpin Tube Type Economizers and Preheaters

Action 7.11g: *In new construction for cycling service, use alternatives to hairpin tube type economizers and preheaters.*

Action 7.11h: *On existing installations, modify the supports on the inlet or outlet headers of each hairpin tube type of preheater and economizer module to incorporate springs.*

Rationale: *Hairpin tube economizers and preheaters with fixed top supports in hot operating conditions substantially redistribute weight between supports. This redistribution is not amenable to reliable, conservative thermal-mechanical analysis to determine the cyclic stresses developed in the hairpin bends and at attachment welds to the headers. Hairpin tube bends, which cannot vent air upwards by gravity, contribute to the indeterminate distribution of dead weight loads and may have an increased risk of deposits and corrosion in the upper bends that are exposed to air and/or vapor locks.*

Potential HRSG Damage: *Thermal fatigue, stress corrosion, corrosion fatigue at upper bends, thermal fatigue or corrosion fatigue at tube welds to headers.*

Figure 7-14 illustrates the typical method of support on many HRSGs that incorporate unvented hairpin-tube type of feedwater preheaters and economizers. The weight of the entire module is supported by fixed supports attached to the top of the feedwater inlet and outlet headers. This comprises an upper inlet header connected to a row of downflowing tubes, a series of rows of inverted U, finned tubes with upper 180° return bends, interconnected by a series of lower return headers, an outlet row of tubes between the final return header and the module feedwater outlet header, and all the water contents. Most of the rows of hairpin tubes are supported by beams installed beneath the upper 180° bends and the latter support beams are each carried by fixed support rods attached to a beam rigidly attached to the inlet and outlet headers. Usually all supports are fixed and rigidly attached to a common structure, from which the inlet and outlet headers and the hairpin bend support beams are all rigidly supported.

Even in the cold as-built condition, the distribution of weight of tubes and lower return headers plus water contents between the individual tubes comprising each row of hairpin tubes is indeterminate because it is practically impossible to fabricate each row of tubes with precisely the same length of tubes. In practice, a large portion of the weight of an individual row of hairpin tubes, return headers and their water contents will be supported by the hairpin bends of the two tubes which have the shortest tube length to their hairpin bend.

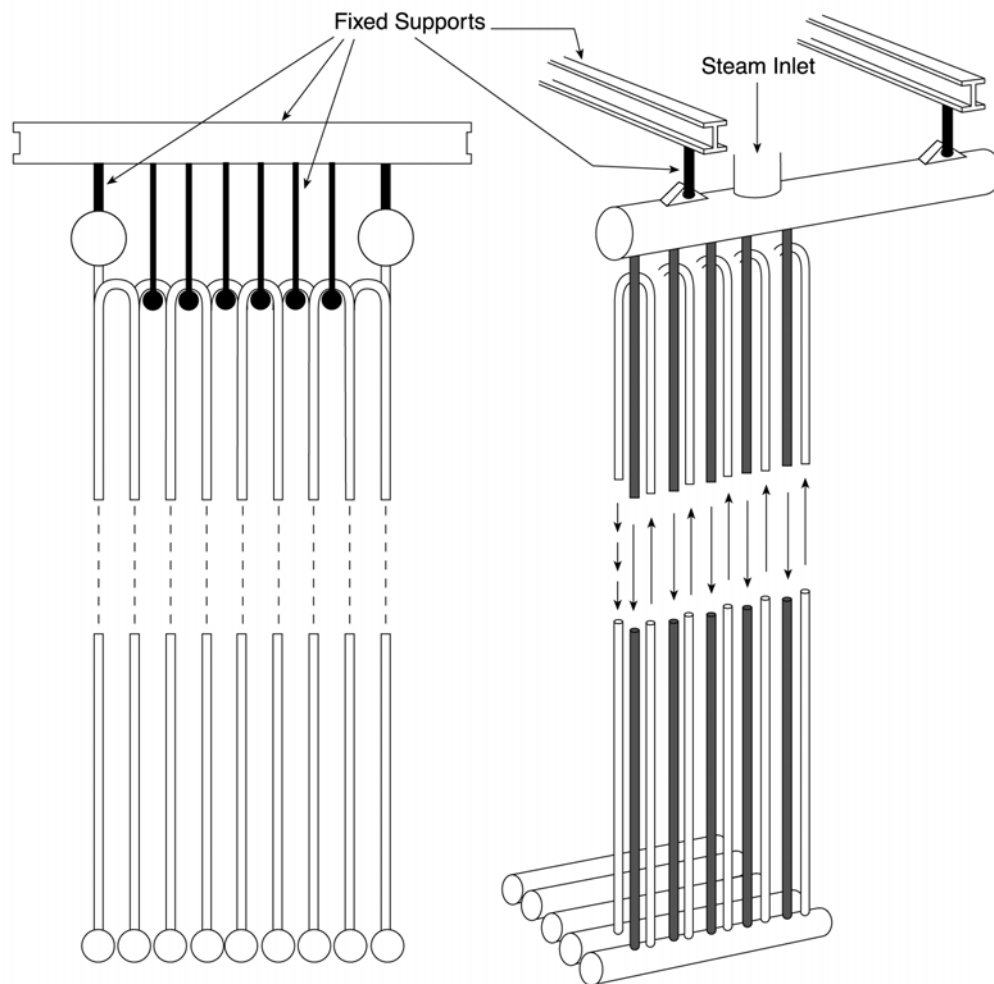


Figure 7-14
The method of support typical of hairpin-tube type of feedwater preheater and economizers.

The intrados of the hairpin bend on most of the somewhat longer tubes in the same row of a module will not be in firm contact with the support beam under the bends and the gravity weight that the unsupported hairpin bends were intended to carry is transferred to, and substantially increases the tensile forces in, those few tubes in the same row that happen to be in contact with the support bar. Furthermore, in multiple row hairpin tube economizers it is possible for some rows of hairpin tubes to have no hairpin bends in contact with their support beam. In this case, the weight intended to be supported in each of the tubes in those rows is also transferred to the few tubes in other rows, which happen to have their hairpin bend in contact with its support beam, thereby further increasing the loads in the few tubes carrying a disproportionate portion of the module weight. In practice, elastic deformation of tubes and support bars will reduce the proportion of module weight carried by the most highly loaded tubes.

Large tensile forces developed in the few tubes supporting a large proportion of the module weight impose a large bending moment as well as a high direct force on the hairpin tube bends. In some instances these have caused gross deformation of the bends due to global plasticity. The

usual fix is to replace failed bends with thicker bends, but these are still vulnerable to localized high, inelastic stresses at the intrados and extrados of hairpin bends. During operating cycles described below, these are potential sources of low cycle fatigue failures at the outer surface, or of corrosion fatigue from pits formed in the inner surface. On HRSGs installed with SCR, the environment at the outer surface of preheaters and economizers is sufficiently corrosive for pitting and stress corrosion if the stresses in the tube bends are high. In general, modifications that enhance the stiffness of a structure increase, rather than decrease, the localized peak stresses.

During normal operation, the distribution of module weight between individual hairpin tubes is even more unpredictable because thermal expansion of individual tubes in each row will differ due to differences in the operating temperature of individual tubes in the same row. Air and/or vapor locks can occur in some of the hairpin bends during startups and on-load operation, which significantly contribute to differences in individual hairpin tube temperatures, as shown in Figures 7-15 and 7-16. Thus when the preheater or economizer is at operating temperature, different tubes will carry the majority of the weight of the module row compared to when the unit was cool. Therefore, those hairpin bends which happen to support a significant part of the module weight during shutdown, but unload when the module is at operating temperature, and vice versa for those bends loaded when at operating temperature, are subjected to at least one thermal-mechanical cycle each startup and shutdown cycle. They are therefore potential sources of fatigue-related failures on cycled HRSGs. The risk of early low cycle fatigue failures is considerably enhanced when tube temperatures fluctuate frequently due to unstable feedwater flow conditions associated with intermittent steaming in some of the hairpin tubes.

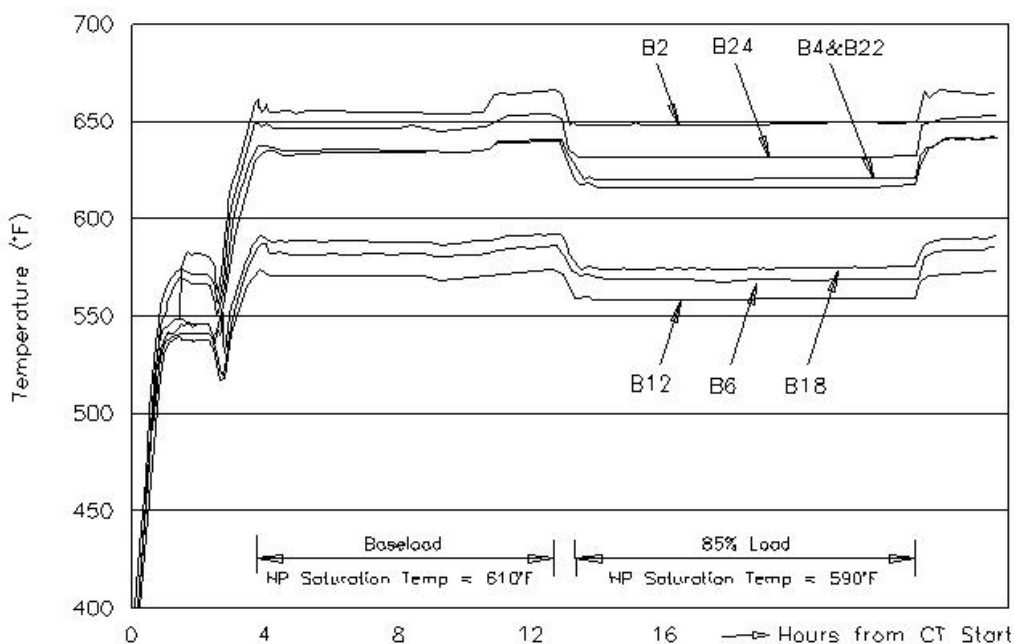
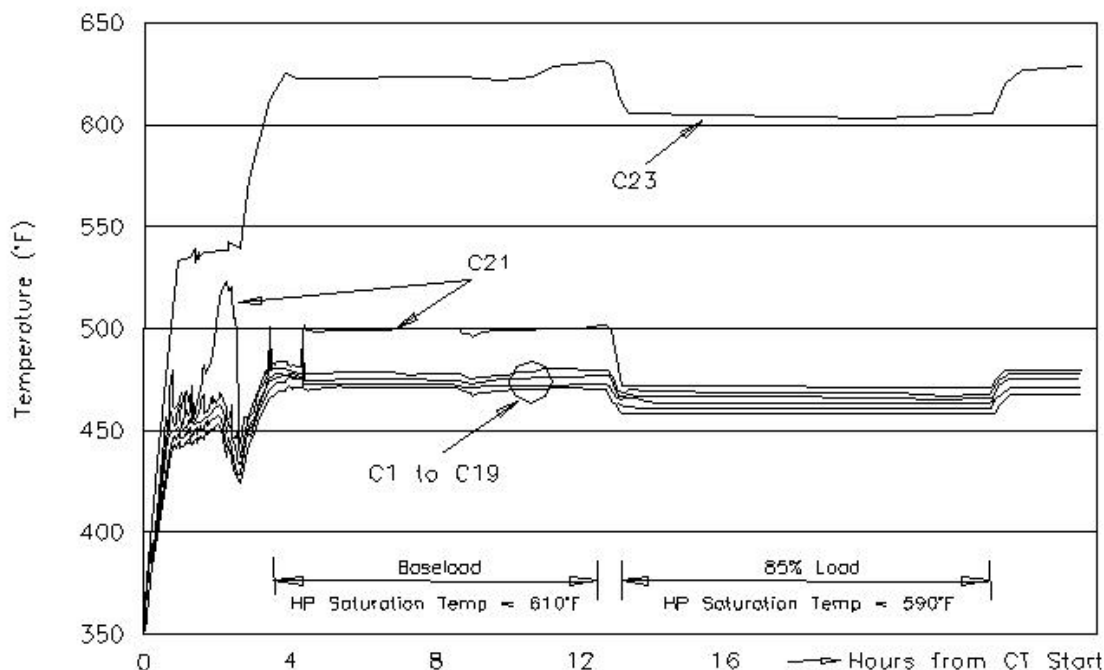


Figure 7-15

Measured tube metal temperatures just below the final hairpin bend and above the roof seal in a 24 tube panel-wide HP Final Economizer Module [7-3].

**Figure 7-16**

Measured tube metal temperatures just below the first hairpin bend and above the roof seal in a 24 panel-wide HP Final Economizer Module [7-3].

There is an additional thermally-induced weight transfer mechanism that further increases the stresses developed in the supported hairpin tube rows nearest to the feedwater inlet and gives rise to even greater uncertainty about the weight distribution and resultant thermal-mechanical stresses in the hairpin bends. Figure 7-17(a) illustrates a typical, as-installed, cold support arrangement for an unvented-hairpin-tube type of economizer or preheater. The weight of all tubes, lower return headers and water contents is notionally transferred at each bend to a support bar and from there to fixed supports.

When on load, the average temperature of the tubes in each successive pass between feedwater inlet and outlet increases by an average of, for example, 5.5°C (10°F) or more, depending on the number of tube passes. Thus, when at operating temperature, the tubes of each successive pass expand thermally relative to the previous pass by approximately the same small increment, assuming equal feedwater temperature rise per pass. As a result, when the HRSG is operating on load, were it not for structural restraints, thermal expansion would cause the preheater/economizer module to change from a rectangle configuration, when all tube were at equal temperature prior to startup, into a trapezoidal shape when tubes are at on load heated temperatures. This unrestrained expansion has been exaggerated in the illustration in Figure 7-17(b).

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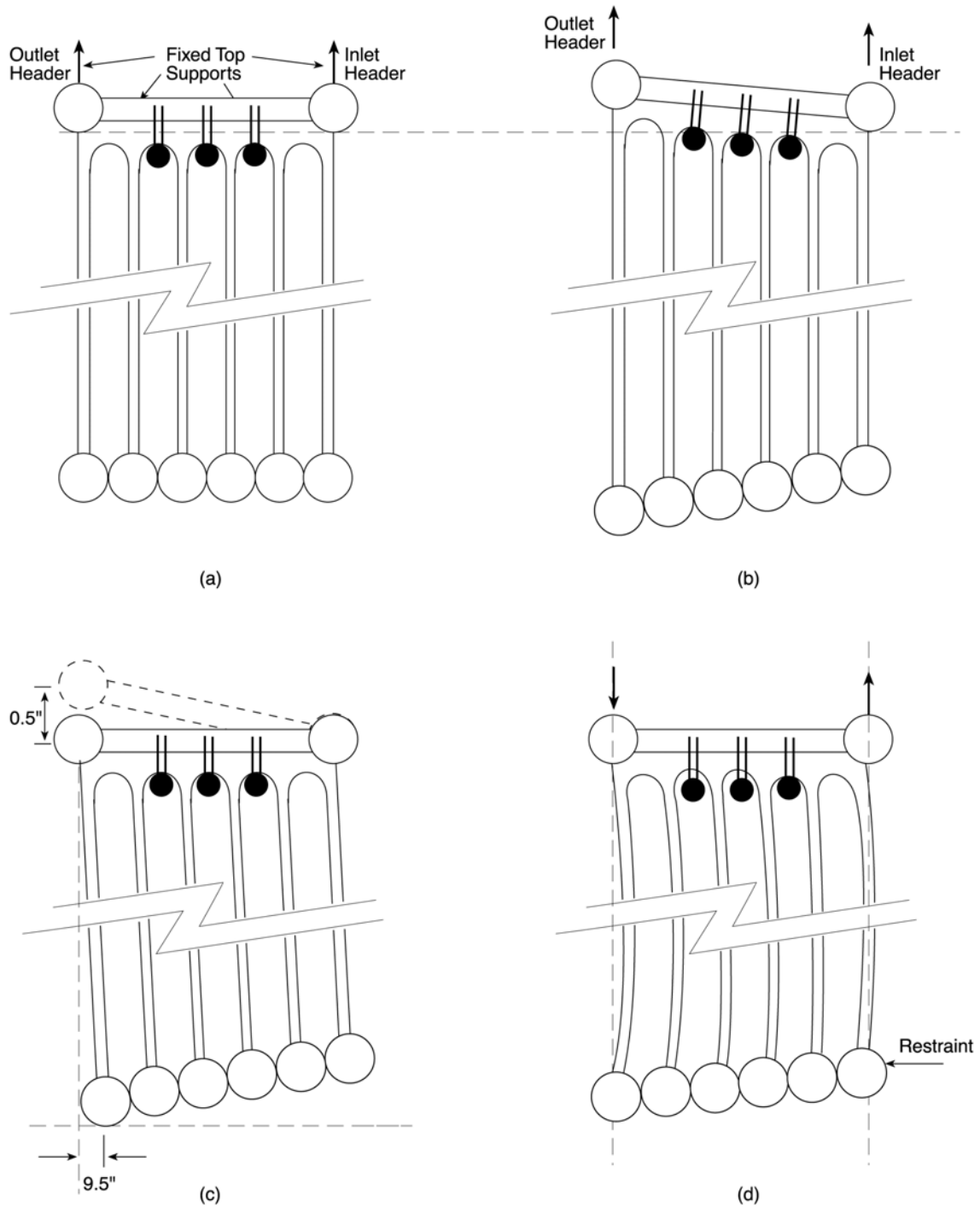


Figure 7-17
Thermally-induced expansion and movements in supported hairpin tube rows nearest the feedwater inlet.

In the heated condition, the upper outlet header wants to expand upwards relative to the inlet header and its own cold set position by, perhaps, on the order of 12 mm (0.5 in.) with each hairpin bend between economizer inlet end to outlet end lifted by a proportional amount. Similarly, the lower return headers expand downwards linearly from inlet row to outlet row by similar amounts. Bottom guides or restraints usually hold the module and tubes in the vertical position and prevent the bottom of the module from swinging back under gravity forces towards the stack by rotation about the inlet header support, Figure 7-17(c).

Thermal expansion attempts to completely unload the fixed supports at the outlet header and, if the entire module was infinitely stiff, would cause the weight of the entire module to be cantilevered from the inlet header supports. In practice, elastic, and possibly inelastic, deformation takes place within the tubes and hairpin bends of the module, but even so, during on load operation the majority of the cantilevered weight of the entire module is supported from the hairpin row with supports beneath its bends that are closest to the feedwater inlet header, Figure 7-17(d). Much of the weight of the entire module and water contents becomes cantilevered from the closest supported row of hairpin bends to the inlet header, adding substantially to the direct tensile and bending stresses imposed on those few hairpin bends in that row that happen to carry the weight of their own row hairpin tubes and return headers. If, as is the case on some installed HRSGs, the outlet header of hairpin tubed economizers is prevented from lifting because the support rod is rigidly attached to its support beam, then the forces and moments imposed on the loaded hairpin support bends is further increased.

For HRSGs already installed, the maximum stresses in the most vulnerable hairpin tube bends can be alleviated by modifying the supports on either the inlet or outlet headers of each preheater and economizer module to incorporate springs. Spring supports should be designed such that there is little change in load distribution between the inlet and outlet header supports between cold and normal operating conditions. This will minimize the changes in forces in the inlet end rows of hairpin tubes. However, the addition of springs at the outlet header supports does not solve the other weaknesses of the hairpin tube type of economizer, and therefore for new installations, which are required to be capable of cycling service, the recommendations outlined above should be followed.

7.12 Economizers Utilizing Shared Headers for Different Economizer Sections

Action 7.12 *Design economizer headers so that tubes of separate sections can expand independently when large temperature differences occur transiently during startups.*

Rationale: *To avoid thermally-induced stresses in tubes of different sections during transients when at significantly different temperatures.*

Potential HRSG Damage: *Thermal fatigue or corrosion fatigue at tube-to-header welds.*

Many HRSGs were, in the past, installed with two economizer sections, e.g., HP and LP, or HP and IP, in the same panels and sharing the same upper and lower headers with a pressure plate inside each header to separate HP from LP or IP feedwater. During every startup drum swell usually necessitates the dumping of water from all steam drums to avoid high drum levels.

During the initial part of startup, there is no feedwater flow through any economizer and, as a result, the stagnant water-filled tubes heat up to gas temperature.

Eventually HP drum swell subsides and feedwater flow then commences through the HP economizer sections rapidly cooling the tubes in the HP economizer sections to the feedwater temperatures. However, at the same time, the LP feedwater flow may be delayed. This phenomenon develops high thermally induced forces of opposite sign in the tubes of the two sections sharing the same upper and lower headers. This process has caused many tube failures that typically begin to occur after about 200 startups. Tube failures are most prevalent at tubes closer to the adjacent economizer section, and in tubes that are offset from the vertical centerline of the header, which develop a bending moment that intensifies the thermal stress at the point of attachment of the tube to the header.

An example of the situation is shown in Figure 7-18 where HP feedwater flow commenced about 30 minutes after CT startup. Commencement of LP feedwater flow had to be delayed until about 73 minutes after CT startup, by which time the LP economizer tubes had heated to 190°C (375°F). Meanwhile, the adjacent HP economizer tubes were cooled by HP feedwater flow to about 121°C (250°F), i.e., about 69°C (125°F) lower than the LP economizer tubes attached to the same upper and lower headers. Temperature differences between HP and LP economizer inlet panel tubes in excess of 83°C (150°F) have been observed on some starts when the start of LP feedwater flow was further delayed.

To alleviate this problem, pressure-part modifications have been made in some units in order to physically separate the lower headers so that tubes of each section can expand en-bloc independently of the other section, as shown schematically in Figure 7-18.

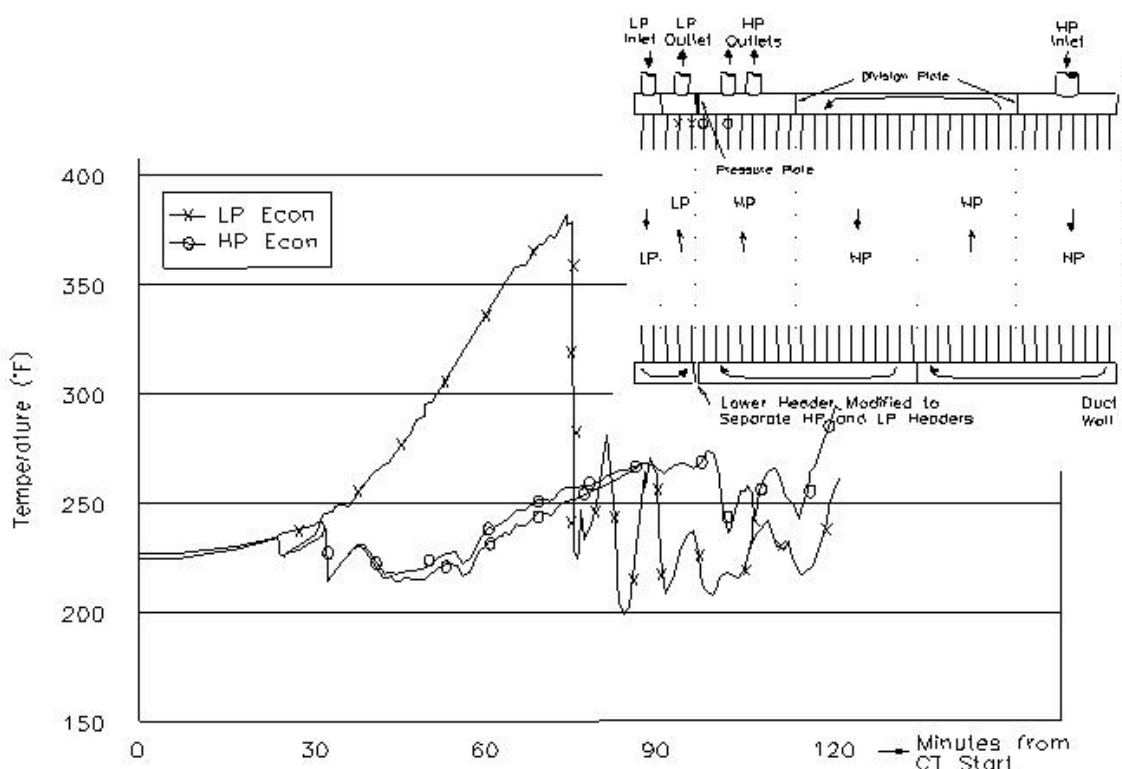


Figure 7-18
Startup for LP/HP economizer feedwater inlet panel installed with shared top and bottom headers [7-3].

7.13 Economizers – Startup Flows in Economizers

Action 7.13 *Include design features to minimize thermal stresses caused by differential cooling of heated economizer tubes on startups.*

Rationale: *Avoid high transient thermal stresses at tube-to-header attachment welds.*

Potential HRSG Damage: *Thermal fatigue or corrosion fatigue at tube-to-header connections.*

A related thermally-induced fatigue mechanism affects many, but not all, economizers assembled from a series of panels arranged with two or more serpentine feedflow passes that share common upper and lower headers with internal division plates to divert the feedwater flow through the labyrinth of passes (Figure 7-19). Usually this “U” or “W” serpentine flow path type of economizer also employs two or three rows of tubes between the same upper and lower headers, which develop higher thermal stresses at tube attachments to the headers. The feedwater inlet panel of serpentine-type preheaters, or of LP, IP and HP economizers are subjected to transiently large thermally-induced stresses in the tubes of the first two passes during startups when cold feedwater flow is introduced into tubes heated to the gas temperature.

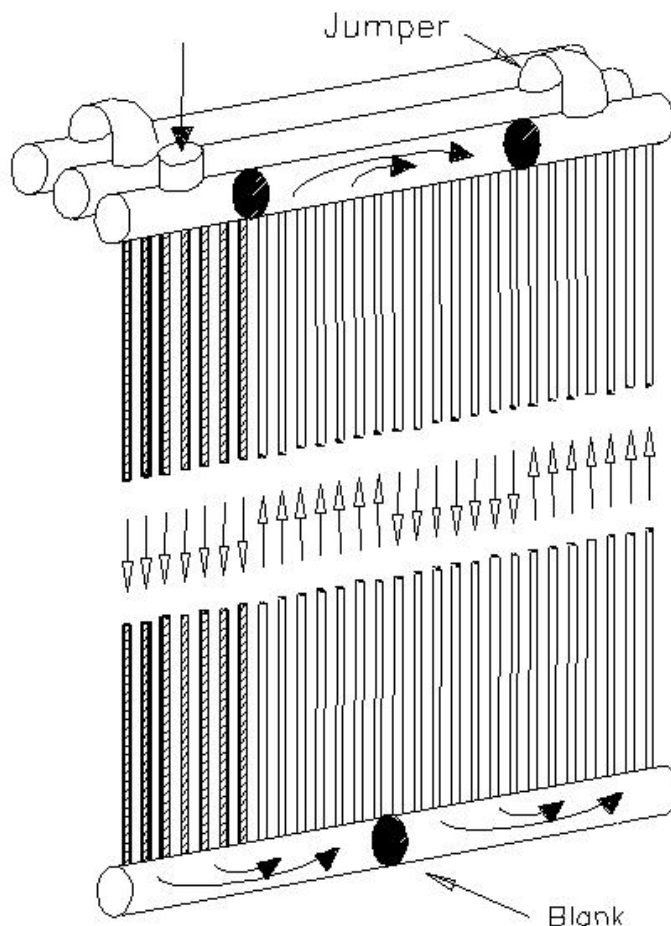


Figure 7-19
Typical multipass low temperature economizer/preheater inlet panel [7-3].

For example, the inlet panel of a small LP economizer section illustrated in Figure 7-20 comprises a downflowing inlet pass of two tubes and an upflowing return pass of three tubes. All five tubes are attached to a lower return header and to a common upper header with an internal division plate to separate the inlet from outlet feedwater. During the typical startup recorded in Figure 7-20, LP feedwater was not required until about 73 minutes after CT startup. By this time, the stagnant inlet and outlet pass tubes had all heated up to about 190°F (375°F). The initial flow of cold feedwater took about one minute to flow down to the bottom of the inlet pass tubes displacing the hot water into the outlet pass tubes. When cold water reached the return header, transiently the inlet pass tubes were chilled to about 52°C (125°F) while the outlet pass tubes were still at 190°C (375°F).

Thus, for a brief period, (which is all that is needed to develop the tube forces and inelastic thermal strains that cause localized plasticity and fatigue damage), the temperature difference between the two passes was about 138°C (250°F). This temperature difference is higher than those that have caused tube failures in economizer panels with shared upper and lower headers. On other units values as high as 149°C (300°F) have been measured.

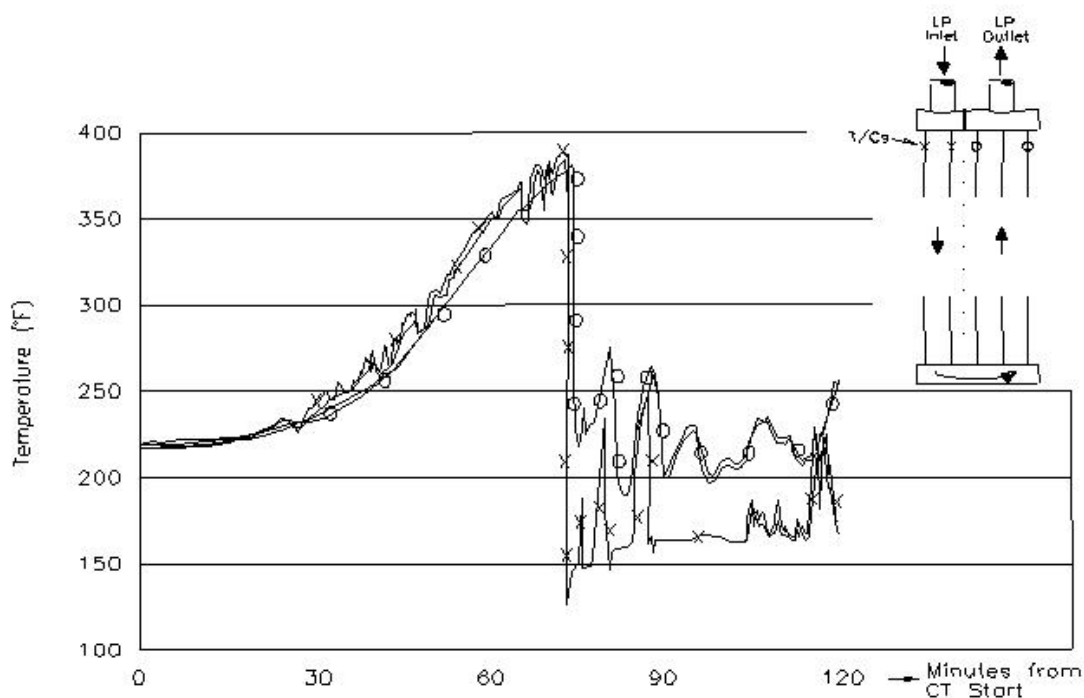


Figure 7-20
Startup temperature profile in a two-pass LP economizer panel with division plate in upper header [7-3].

On installed HRSGs, which have serpentine-type economizer panels, it is usually impractical to modify the design of the economizer to eliminate this potential source of premature fatigue failures. The problem can be mitigated if some means can be devised to preheat the incoming feedwater, or re-circulate feedwater through the economizers during the startup period when feedwater cannot be fed to the steam drum, or by operating procedures that permit earlier feeding of water to the drums. These options involve significant modifications for many installed units.

For new installations, the weakness can be mitigated by locating the inlet to the first pass of lowest temperature economizers/preheaters to the lower header, which permits the physical separation of the inlet header from the lower header of tubes in subsequent passes in the same panel (Figure 7-21). This eliminates the most severe transient thermally induced tensile forces in tubes of the first pass by allowing them to contract when chilled as cold feedwater is introduced.

Transient temperature differences still occur between tubes of subsequent passes after feedwater flow is initiated. However, by the time the feedwater flows down the second pass its temperature has already increased by of the order of 42 to 56°C (75 to 100°F), thereby reducing the transient difference between tubes of second and third passes to about 83 to 111°C (150 to 200°F). This temperature difference would probably still be large enough to develop thermal fatigue stresses in tubes of second and third passes large enough to cause early fatigue failures, especially in offset tubes.

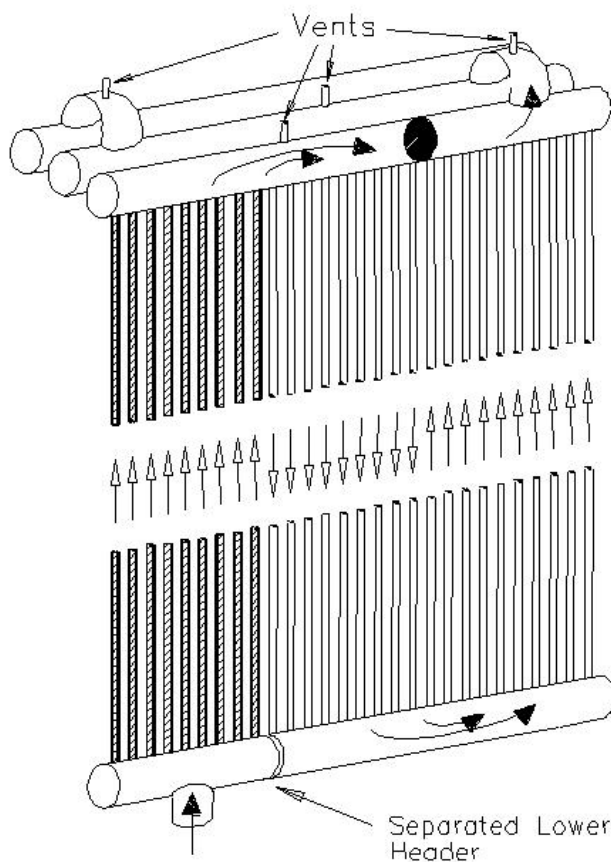


Figure 7-21
Design of low temperature econ/preheater inlet panel for cycling

Therefore, for units intended for cycling service using this type of economizer, it is necessary to install means to eliminate the introduction of cold water directly into a hot LP economizer/preheater during startups. Condensate recirculation from preheater/LP economizer outlet back to its inlet is one such means. Another is the provision of a separate deaerator capable of supplying deaerated feedwater at about 121°C (250°F). This option has the additional advantage of reducing the risk of pitting corrosion in economizer tubes by stagnant, poorly-deaerated water introduced during feed water flow interruptions at startups.

Hairpin type economizers or preheaters (Figure 7-14) are equally vulnerable to a similar effect when cold feedwater is first admitted during reloading of the CT after startup. The transient differential contraction of the colder downflowing tubes lifts the hotter downstream rows of hairpin tube bends off their supports. This transiently transfers a large portion of the weight of the module to inlet row tubes and to the earlier rows of hairpin bends.

This problem can be mitigated for preheater/LP economizers of hairpin tube type design on existing installations by installing spring supports for the inlet headers. For new installations, the remedies suggested for serpentine preheaters/LP economizers are equally applicable for the hairpin tube type of preheater.

7.14 Recirculation in Economizer and Preheater Tubes

Action 7.14 *Include means to prevent buoyancy effect such as improved side-wall baffles to reduce hot gas leakage, increased tube internal pressure drops, and/or installation of small vents on upper headers of economizers and preheaters.*

Rationale: *Large differential tube temperatures, caused by reversal of flow in some tubes of downflowing passes when buoyancy forces exceed the tube pressure drop forces, results in high transient thermal stresses.*

Potential HRSG Damage: *Thermal fatigue or corrosion fatigue in tube-to-header connections.*

Temperature measurements at the top and bottom of tubes in the first downflow pass of serpentine-type economizers/preheaters have highlighted that buoyancy effects cause some tubes to reverse flow direction and recirculate feedwater from the lower return header back to the upper inlet header.

The phenomenon occurs in tubes which have lower pressure drops between tube inlet and outlet, being furthest from the second pass in the lower header and also from the inlet branch on the upper header. Thus flow rate through these tubes is lower, and temperature rise and upward buoyancy forces higher. It is suspected that an air pocket may remain trapped at the blind end of the header and increases the system resistance from inlet branch to end tubes. Tubes adjacent to the duct sidewall may also pick up more heat from leakage of hot gas between tubes and duct wall.

Figure 7-22 shows an example of this phenomenon. As shown, the tube at the end of the header adjacent to the duct sidewall started to recirculate heated feedwater back to the inlet header immediately after the HP feedwater flow commenced 32 minutes after CT startup. The same behavior was evident to a slightly lesser extent in the adjacent tube and, to a progressively reducing extent, also in the third tube from the header end for about 20 minutes after the HP feedflow commenced. The feedwater recirculation phenomenon disappeared after feedwater flowrate increased above 50% of baseload flow provided also that rapid fluctuations in HP feedwater flow rate remained below +/- 25%.

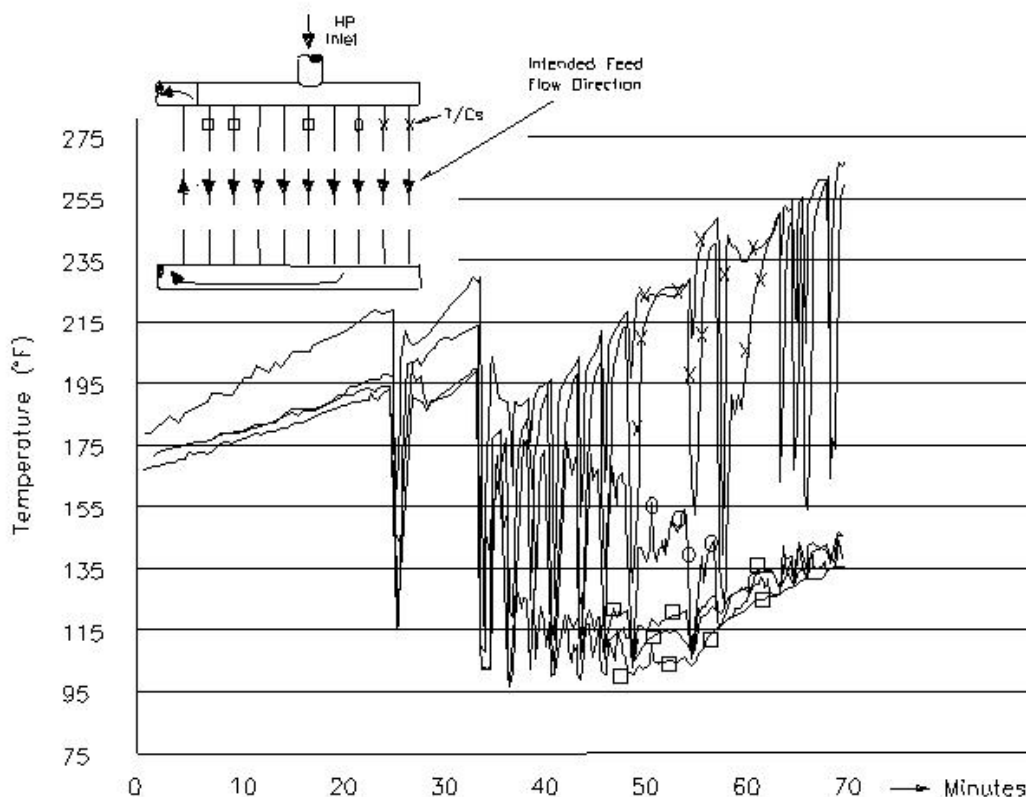


Figure 7-22
Inlet pass tubes of HP economizer with flow recirculation in tubes.

In this case, the difference in average temperature of recirculating tubes and tubes flowing in the intended downward direction is about 36°F (65°F), being half the temperature difference measured at the top of the tubes. Although this is lower than tube temperature differences developed between economizer tubes by other undesirable design features, there are nevertheless concerns that the large number of thermal cycles experienced during each startup may lead to thermal fatigue failures in the affected tubes when the operating regime for the unit changes from baseload to cycling service.

Practical options to attempt to eliminate this design deficiency on installed units are limited. Improved baffles to reduce leakage of hot gas between tubes and duct sidewall and the installation of small vents on all upper headers of economizers may mitigate the problem. For new installations more attention must be given to ensuring that pressure drops through all downflowing tubes have adequate margin to overcome the upward buoyancy forces. It is particularly important to ensure that economizers and preheaters which employ small diameter headers are installed with sufficient interconnecting pipe jumpers between successive headers to achieve reasonably uniform flow rates through all of the downpass tubes (Figure 7-23).

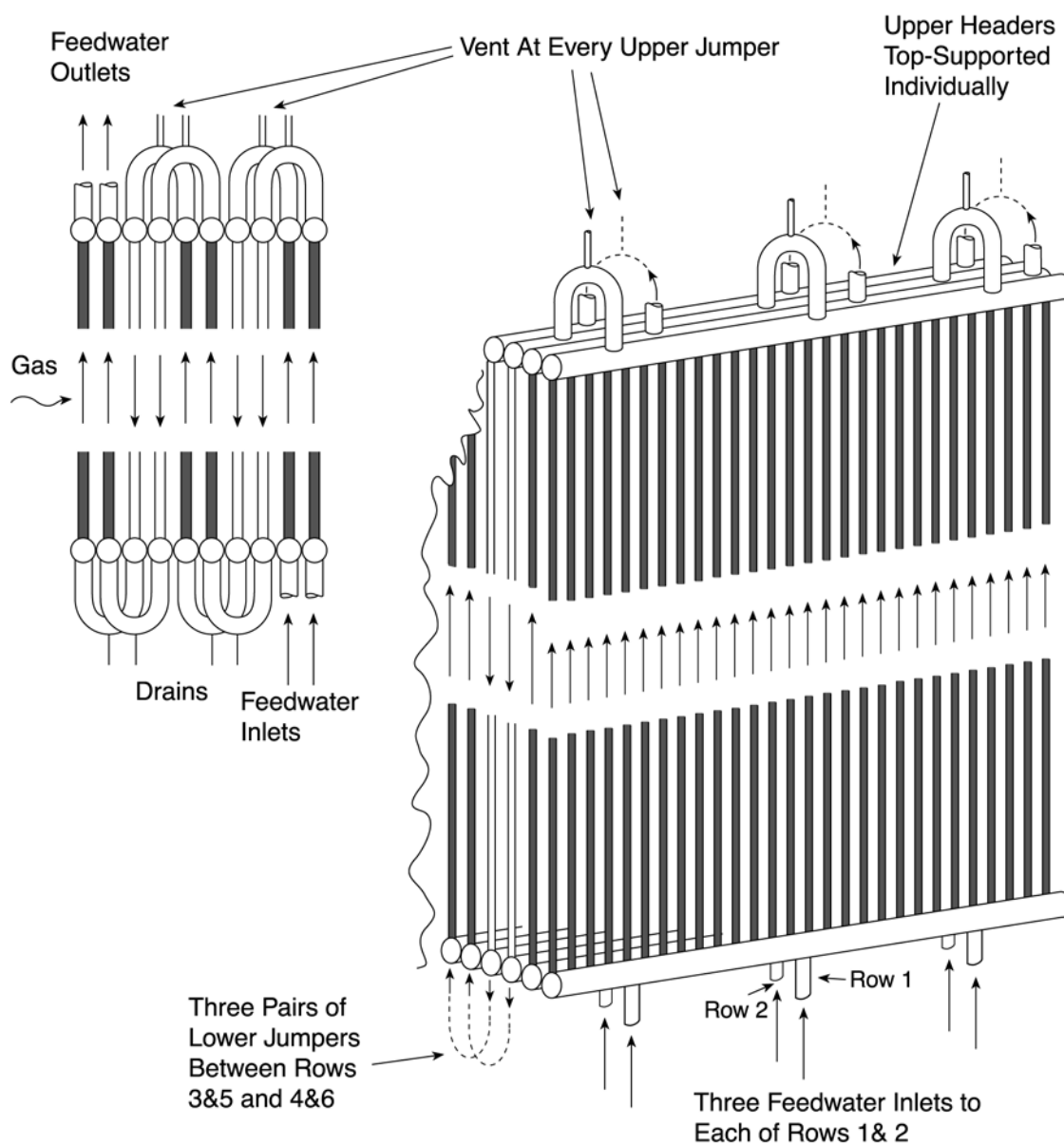


Figure 7-23
Arrangement of interconnecting pipe jumpers to achieve uniform flow throughout the downpass tubes.

7.15 Economizer/Preheater and Evaporator Drains

Action 7.15a: Prevent leakage past isolating valves of lower header drains of economizers/preheaters to the lower headers of higher temperature sections by separately double isolating and not interconnecting drains from lower headers.

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Action 7.15b *Ensure all sections in the HRSG have no low points that cannot be completely drained by gravity.*

Rationale: *Leakage of cooler feedwater into hotter sections causes large tube-to-tube temperatures and significant thermal stresses in tubes and bends. Ability to completely drain all sections during long shutdowns is essential in colder climates to prevent freeze damage.*

Potential HRSG Damage: *Thermal fatigue or corrosion fatigue in tubes at attachments to headers or in bends.*

Leakage past isolation valves in interconnected drain pipes can cause tube-to-tube temperature differences in outlet row tubes of economizers and preheaters that are large enough to lead to thermal fatigue related failures on cycled HRSGs.

The drains from economizers and from evaporators must be capable of completely emptying the contents of these sections of the HRSG when the unit is to be emptied for maintenance. In order to ensure no risk of freeze damage to pipes, it is important to ensure that all drains from lower headers and interconnected pipes on all HRSG sections are from the lowest points and fall continuously to the point of release from the system.

All drains, vents and other connections to the HRSG steam and feedwater systems that may need to be opened or closed during normal startups and shutdowns should be provided with motivated isolation valves for remote operation through the DCS.

Drains that are only used for maintenance purposes and which never require operation during startups and shutdowns after overnight or weekend periods when the unit is scheduled off load can utilize manually operated duplicate isolation valves.

7.16 Geometry Effects and Layout Arrangements

7.16.1 Stresses Influenced by Tube-to-Header Design

Action 7.16a: *Understand the relative merits and limitations of alternative tube-to-header attachments. Specify attachments that will achieve the requisite extent of cycling service for all sections of the HRSG.*

Action 7.16b: *Avoid offset tube attachments where possible in designing tube-to-header connections.*

Action 7.16c: *For tube and header arrangements with the potential for high thermally induced stresses, such as offset tube attachments, perform conservative analysis to determine where superior strength attachment are required.*

Action 7.16d: *Ensure that panel fabrication and inspection requirements are appropriate for the type of tube-to-header arrangement used and the extent of cycling service anticipated.*

Understand that panels with a single row of tubes attached to an upper and lower header provide the best access for performing tube-to-header welds.

Rationale: Utilization of inappropriate type of tube-to-header attachments, fabrication and heat treatment processes or inadequate inspections, increases the risk of tube failures at the attachment welds, especially on HRSGs intended for cycling service.

Potential HRSG Damage: Thermal fatigue, creep fatigue or corrosion fatigue at tube-to-header attachment welds.

Figure 7-24 illustrates four different types of tube-to-header attachment arrangements used on HRSGs. Each of these designs has distinct advantages and disadvantages, which are listed in Table 7-4. For thin headers, the forged nipple design (Figure 7-24c) is probably optimal from a cyclic life point of view. For thicker headers (reheater outlet or HP superheater), the forged nipple design becomes more difficult to fabricate and may require undesirable increases in header diameter, wall thickness and tube spacing in order to provide the necessary clearances for the nipples. If optimal fatigue performance is required, the set stub tube with a partially set connection with an engineered thickness transition and a complete joint penetration weld (made using optimal procedures and quality control) (Figure 7-24d) is probably the best choice. Where the tubes are not offset from the header axis and the actions discussed throughout the earlier sections to minimize high transient or steady state stresses are taken, the low cost set-on welds may be the best choice.

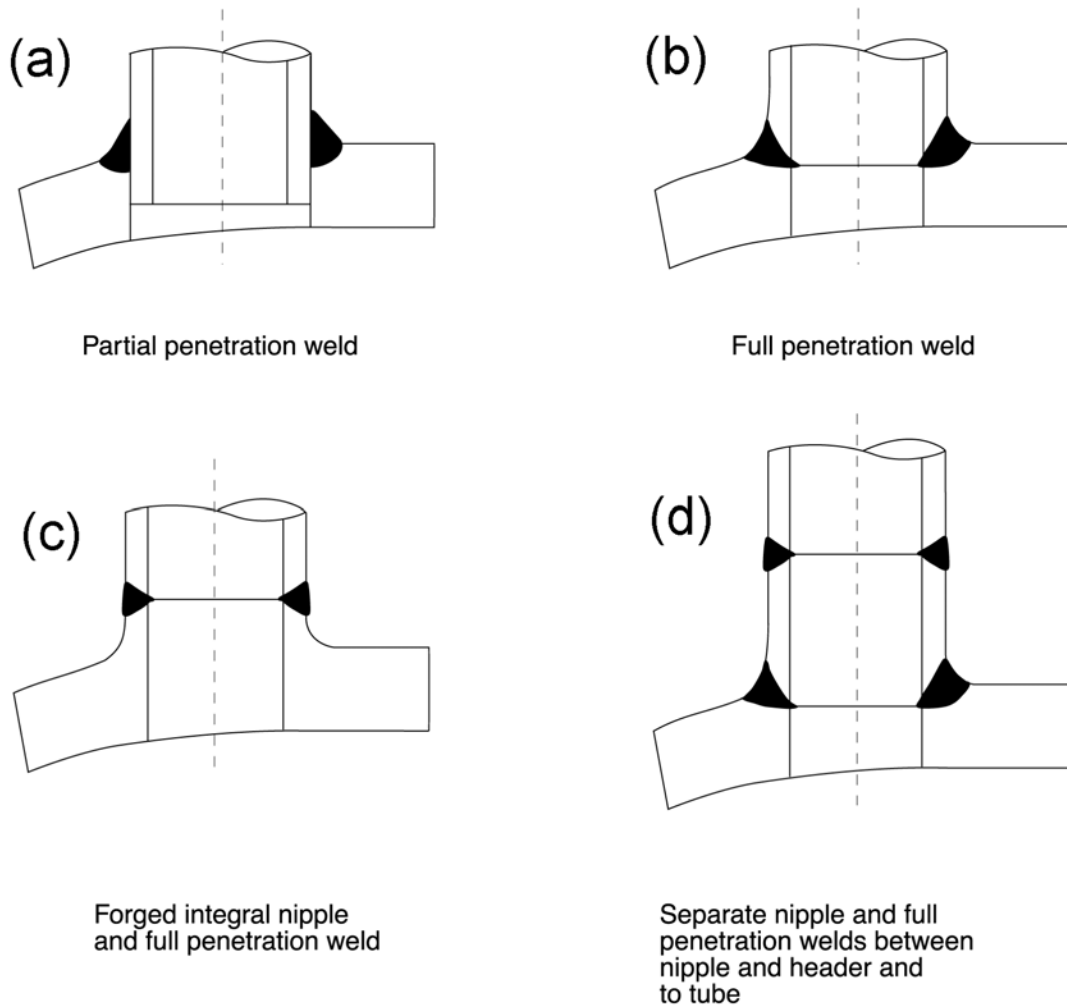


Figure 7-24
Various tube-to-header attachment geometries

Table 7-4
Attributes of Several Tube to Header Connection Designs

Connection Design	Advantages	Disadvantages
“Set-in tube” with partial joint penetration groove/fillet weld [Figure 7-24(a)]	• Low manufacturing cost • Doesn’t require precise fit up • Tube can be cut to standard length • Excessive weld root reinforcement isn’t an issue	• Contains a “crevice” which may promote crevice corrosion especially in water touched headers or lower SH/RH headers (which may be exposed to condensate) • May have poorer fatigue performance than a complete joint penetration weld • The weld root quality can’t be easily verified by NDE • Creates a severe thickness transition between the tube and header which may exacerbate the local thermal transient stresses • Post weld heat treatment and thermal straightening are difficult
“Set-on or partially set-in tube” with complete joint penetration groove/fillet weld [Figure 7-24(b)]	• With good weld quality should have better fatigue performance than the set in, partial joint penetration design	• Fatigue performance may be dependent on weld root quality which is difficult to determine with conventional NDE • Requires precise fit up • Prone to incomplete joint penetration and excessive root reinforcement discontinuities • Creates a severe thickness transition between the tube and header which may exacerbate the local thermal transient stresses
Forged integral nipple with complete joint penetration groove weld [Figure 7-24(c)]	• Only requires a single easily welded butt connection • Has an inherent thickness transition that may reduce the magnitude of the local thermal transient stresses acting on the weld • Eliminates the header bowing associated with the tube-to-header attachment welding • May eliminate the need for post weld heat treatment	• Expensive, especially for the thicker walled outlet headers. • May require larger diameter, thicker headers to provide the borehole spacing required for the spacing required for nipple extrusions
Header stub tube connected to the header with a partially set in, complete joint penetration weld then joined to tubing with a complete joint penetration groove weld [Figure 7-24(d)]	• Allows furnace post weld thermal straightening of the header and post weld heat treatment of the stub tube and header welds • Allows easy inspections of the root of the stub tube-to-header weld • This approach is amenable to the use of an “engineered stub tube” to provide an optimal tube-to-header thickness or material transition	• Requires two welds • Both welds prone to inadequate penetration and excessive root reinforcement (burn-through discontinuities) which must be prevented to assure good fatigue performance

7.16.2 Forces and Moments from Interconnecting Pipes

Action 7.16e: *Confirm that bending stresses at tube-to-header attachments caused by the terminal forces and moments applied by pipes to the headers will provide acceptable joint lifetimes. Modify piping if necessary to verify they are all compatible with the fatigue design life specified for the HRSG.*

Rationale: *This can eliminate a significant contributor to tube failures at header attachments.*

Potential HRSG Damage: *Creep fatigue or thermal fatigue or corrosion fatigue at tube attachments to headers.*

It is important to ensure that interconnecting pipe connections to headers do not apply rotational moments to headers large enough to develop significant bending stresses in the tubes attached to those headers. Stresses thus generated would be additive to the bending stresses that may already be developed by the header and tube row arrangements.

Upper headers are generally fixed at their supports and therefore the pipes connected to upper headers require adequate flexibility to accommodate expansion from cold to hot conditions in the pipes and the headers, without developing significant rotational forces and moments on the upper headers.

Pipe interconnections between lower headers require greater flexibility to accommodate not just their own expansion from the cold to hot condition, but also the differential downward expansion of the interconnected lower headers by tubes that are heated to different operating temperatures. It is important to conservatively calculate the bending stresses at lower tube-to-header attachment welds caused by the maximum predicted pipe forces and moments at terminal connections to lower headers. Then, if necessary, the design of interconnecting piping should be modified to ensure that the resultant bending stresses at tube attachments to the headers are compatible with the intended design cyclic life of the HRSG.

7.16.3 Design and Location of Material Transition Welds between P22 and P91/T91

Action 7.16f: *Avoid material transitions between headers and tubes.*

Action 7.16g: *Locate P22 to P91 welds where bending moments and axial stresses in the pipes are low and where the transition welds are accessible for periodic NDE.*

Action 7.16h: *Allow space for, and utilize a P91 transition piece to match pipe thicknesses at, the P22/P91 transition weld.*

Action 7.16i: *The design of transition welds should account for the reduced stress rupture and creep-fatigue properties of the weld in its final post weld heat treated condition.*

Rationale: Minimize/delay the possibility of Type IV or creep fatigue cracking at P91 welds by reducing axial and radial stresses at the transition welds.

Potential HRSG Damage: Early Type IV or creep fatigue cracks in P91 transition welds.

P91 material is susceptible to a mode of cracking referred to as Type IV cracking. Type IV cracks are creep cracks that initiate and grow in the portion of the weld heat affected zone furthest from the weld interface. Transition welds are particularly vulnerable to the Type IV cracking phenomenon. Type IV cracks at welds are potentially dangerous because they initiate beneath the pipe surface and depending on the weld prep geometry can become dangerously long cracks by the time they can be visually detected at the outer surface of the pipe.

The propensity for Type IV cracks to develop in other susceptible low alloy steels has been successfully lowered by reducing bending moments and axial forces at the welds and additionally by using a transition piece to avoid thickness discontinuity at the transition weld between the materials of dissimilar strength and thickness.

Greater importance needs to be given to the above requirements and also space requirements for proper management of condensate drainage in the congested space usually allowed between the bottom of the HRSG casing and the floor slab. The arrangement illustrated in Figure 7-6, locates each of four transition welds between the thick P22 pipe and the much thinner P91 in a short, relatively stiff straight pipe attached to the inlet header above. The manifold pipe and inlet headers will heat and cool at different rates, which applies bending moments at the transition welds. Water from passing attemperator control valve or from condensation in tubes may bow the manifold pipe thereby applying additional bending moments to the transition welds. There is rarely sufficient space to accommodate the condensate pot or to provide fall to the drain point which are essential to ensure condensate cannot lie along the bottom of the manifold.

When transition welds are required, the applied and design allowable stresses must be evaluated in more detail. A common error in the design of transition welds is to ignore the large weld strength reduction factors associated with these welds. As shown in Figures 7-25 and 7-26, the stress rupture properties for P91 welds are well below the properties of P91 parent material. P91-to-P22 transition welds can have even lower stress rupture properties, which are influenced by the joint and weld design, the welding procedure and the post weld heat treatment. It is important that the designer and fabricator work together to develop appropriate welding and post weld heat treatment procedures that are consistent with the assumed weld performance factors used in the design calculations.

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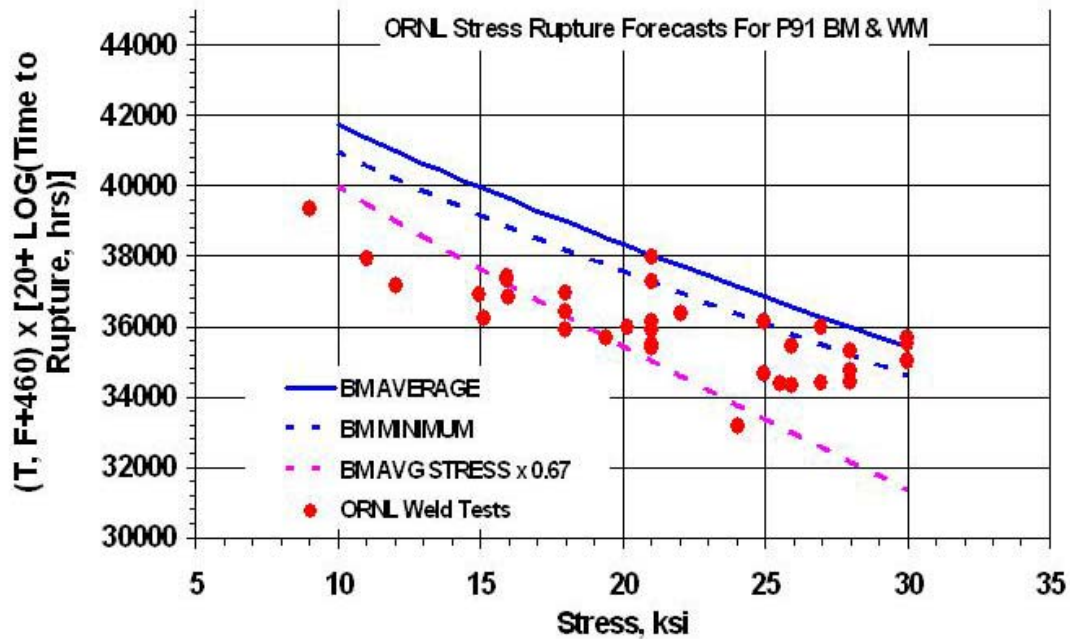


Figure 7-25
Stress rupture properties for P91 base metal and weld metal.

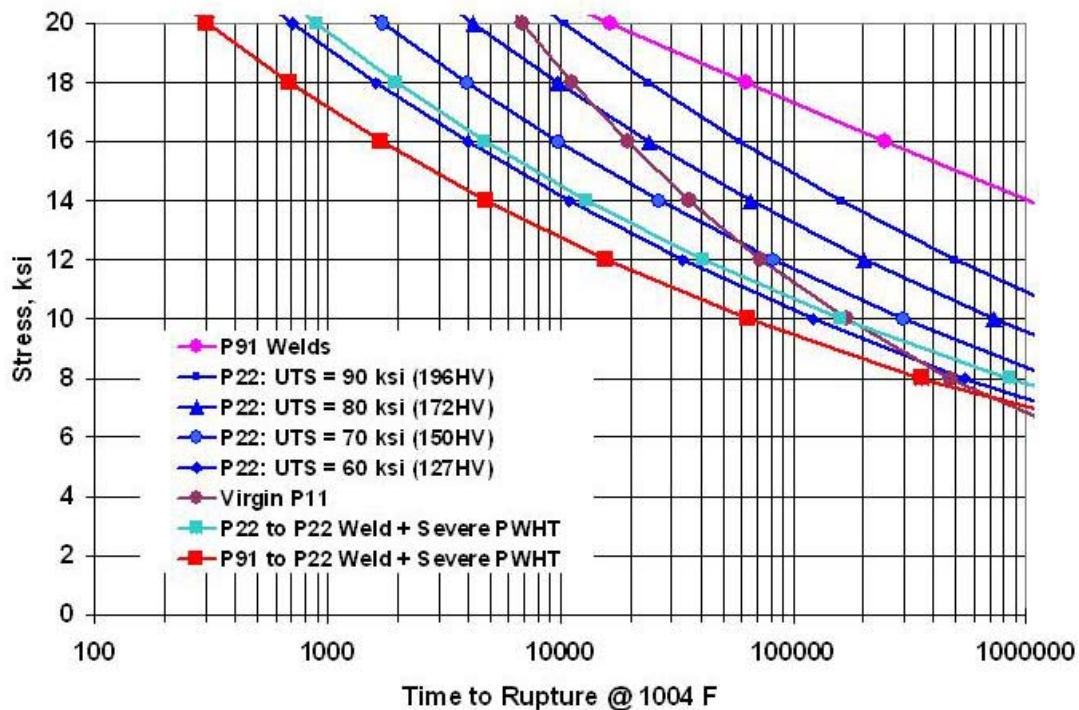


Figure 7-26
Stress rupture properties of P91, P22 and P11 materials and welds.

7.16.4 Shared Headers with Internal Pressure Plates

Action 7.16j: *Avoid shared headers with internal division plates for cycling service.*

Action 7.16k: *For HRSGs intended for cycling, verify that the division plate integrity is compatible with the design cyclic life using thermal-mechanical analysis based on measured transient temperatures.*

Rationale: *The internal division plates may heat and cool at a different rate to the header wall on each side and may develop thermal stresses in the welds between plate and header wall that lead to premature fatigue-related failure.*

Potential HRSG Damage: *Thermal fatigue, corrosion fatigue.*

Internal division plates are used by some designs of HRSG in HP superheaters and reheaters and in economizers/preheaters. Failure of the division plate would not be detectable until it had progressed sufficiently to have a discernable impact on the performance of the HRSG. Repair would be difficult.

7.17 Panel and Module Support Arrangements

Action 7.17a *Arrange panel supports within modules to minimize thermally induced stresses in individual tube rows.*

Action 7.17b: *For cycling HRSGs, use flexible supports for top supported panel arrangements that develop differential expansion forces between tube rows of the same panel when expanded.*

Rationale: *Minimize thermal-mechanical stresses developed in tubes when expanded from cold to hot operating conditions, either by tube row-to-tube row temperature differences, or by redistribution of weight between panels within a module assembled from several interconnected panels.*

Potential HRSG Damage: *Creep fatigue, thermal fatigue, or corrosion fatigue in proximity to tube-to-header attachments.*

In large HRSGs, all headers and tubes are top-supported, usually by fixed supports. Tubes expand axially in the downwards from the fixed top headers and the lower headers are usually provided with guides that permit free downward expansion but maintain the panel alignment transversely and in the direction of gas flow.

Modules may be assembled such that all tubes in each independently top-supported panel are at similar temperatures when at hot operating conditions, as in Figures 7-1, or 7-23. In this case, fixed top supports do not introduce any support/restraint-related stress in the tubes when they expand from cold to hot conditions. Not all designs of HRSG arrange panels in this way. For example, some designs of HRSG HP superheaters and reheaters are constructed from panels that

have both the inlet and outlet headers at the top with a row of downflowing inlet pass tubes, bottom return header and upflowing row of outlet pass tubes, Figure 7-27. Usually both of the upper headers have fixed supports. In this arrangement case, when heated from cold to operating conditions, the difference in temperature between outlet and inlet pass tubes develops significant forces in the two tube rows. The thermal stresses developed by these forces in all tubes in the row, or in individual tubes quench cooled by condensate during startups, are considerably intensified by the bending moments at the attachment of those tubes that are offset from the headers and at tube bends attached to the headers.

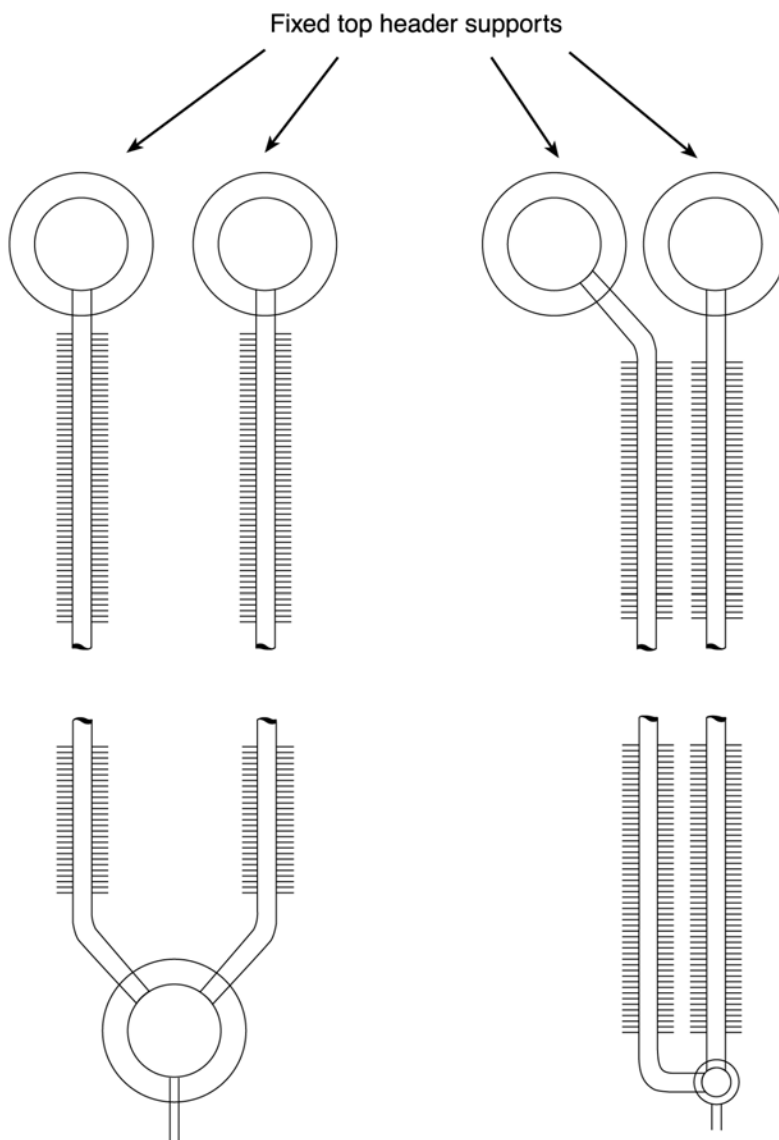


Figure 7-27

Tubing arrangement with inlet/outlet headers on top with a bottom return header.

For cycling operation, it is recommended that the supports are modified to incorporate springs at either the inlet or outlet header support to reduce the thermal stresses developed at tube attachments when the panel is at operating temperature.

7.18 Design for Minimizing Vibration and Noise Due to Vibration

Action 7.18 *Design all parts of the plant to minimize vibrations, particularly HRSG walls and external pipelines.*

Rationale: *Minimize fatigue damage and reduce noise levels.*

Potential HRSG Damage: *Flow-induced vibration fatigue.*

Vibration and noise are frequent problems in the operation of HRSGs. Although there are a number of causes for the problems resulting from vibration in the inlet plenum and heat exchanger sections of a specific boiler, the most common type of problem occurs in the heat exchangers, which is commonly known as “vortex shedding vibration”. It is a phenomenon that results when the frequency at which the small eddy current of flue gas trailing the tubes over which it flows is nearly the same as the natural frequency (transverse acoustic frequency) of the flue gas at that location for any of the first three or four harmonics. The natural frequency is dependent on flue gas characteristics and the dimensions of the enclosure, where the frequency of the standing wave can be predicted by the equation [7-1]:

$$f_n = N \cdot C / 2W$$

Equation 7-1

where,

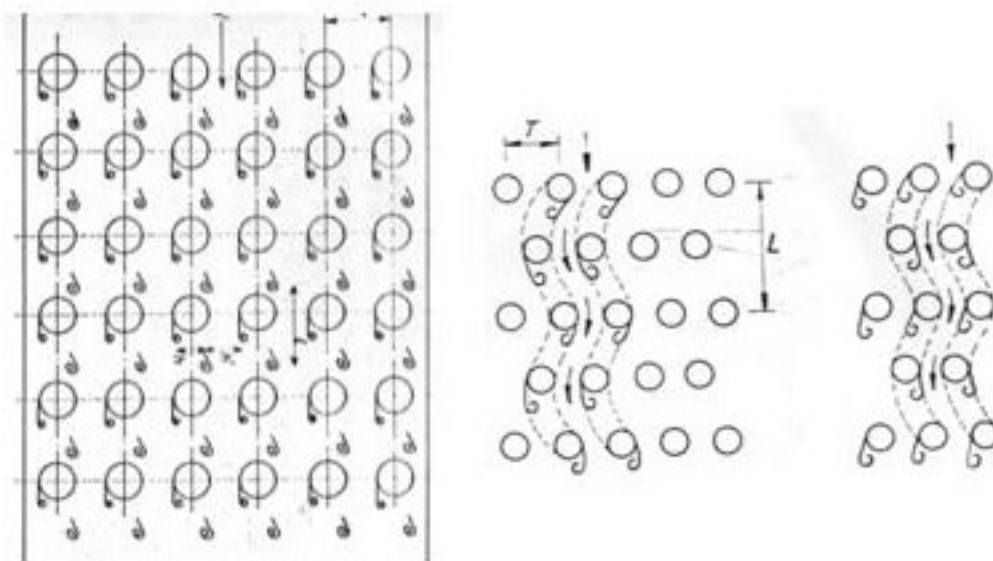
f_n = acoustic frequency

N = mode number, dimensionless integer

C = velocity of sound in the fluid surrounding the tubes

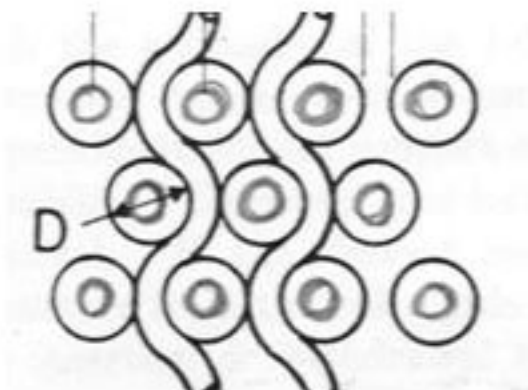
W = characteristic width or length of the acoustic chamber (distance between enclosure walls).

Figure 7-28 is a schematic representation of the vortex shedding process applicable to HRSG design.

**Figure 7-28**

Schematic of von Karman vortex streets over in-line and staggered tube fields [7-6]

This problem is corrected by installing baffles that will effectively change the dimensions of the enclosure and thus change the natural frequency of the flue gas and eliminate the problem. An illustration of a typical baffle arrangement is shown in Figure 7-29, which depicts a baffle-to-tube fin contact, not a baffle-to-base tube contact to prevent contact wear. The installation of sinuous baffles, fabricated from suitable materials to withstand the operating temperatures, throughout a vertical gas path HRSG is depicted in Figure 7-30.

**Figure 7-29**

Anti-vibration baffle in staggered tube heat exchanger [7-5].

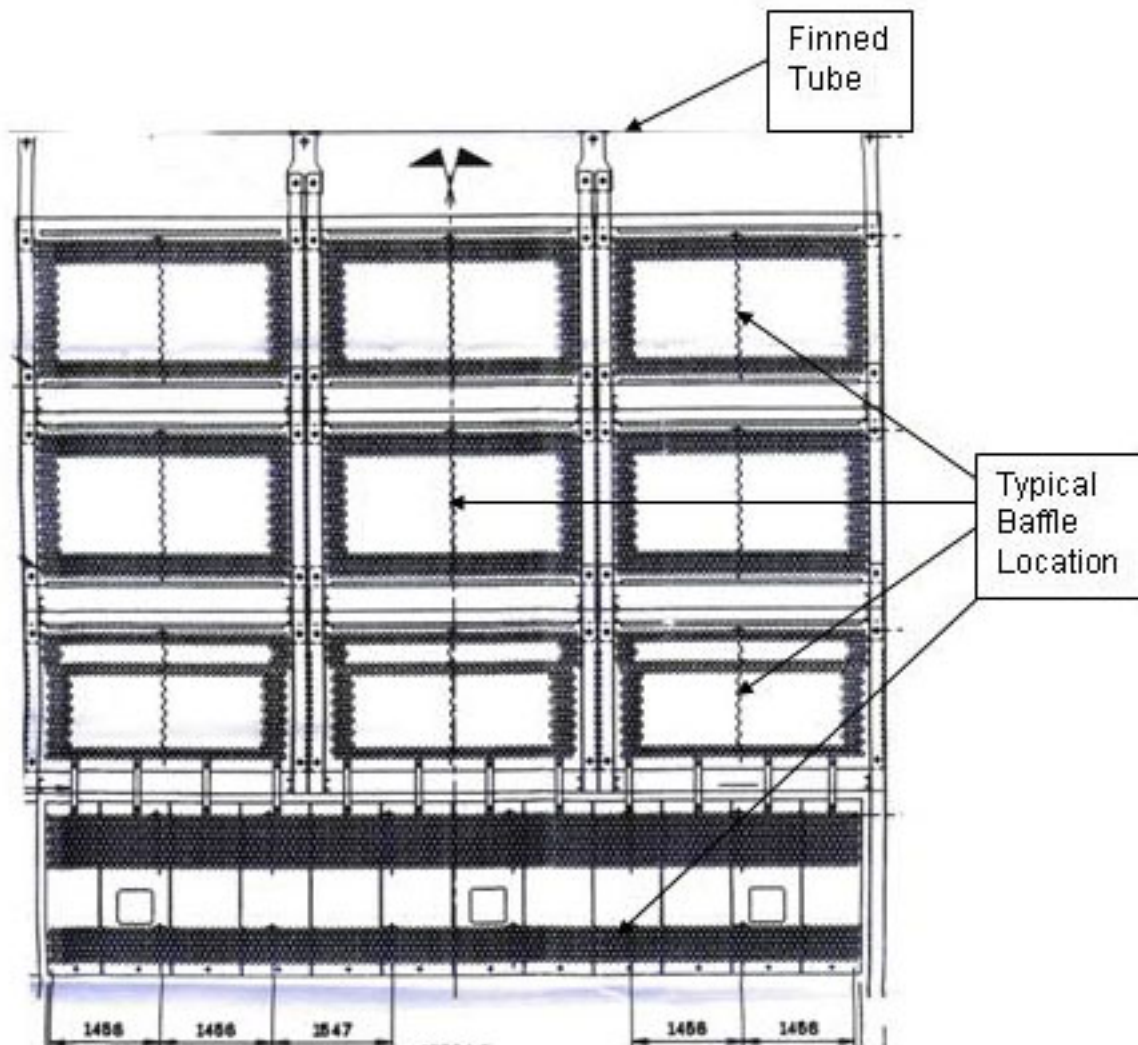


Figure 7-30
Anti-vibration baffle arrangement in vertical gas path HRSG [7-7].

7.19 References

- [7-1]. Pearson, J.M., Anderson, R.W., "Reliability and durability of large heat recovery steam generators", *Proceedings of Institution of Mechanical Engineers, (U.K.)*, Volume 213, Part A, pp 151-168.
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[7-5]. Eisinger, F.L., “Prevention and Cure of Flow-Induced Vibration Problems in Tubular Heat Exchangers”, *Transactions of the ASME*, Volume 102, May, 1980.

[7-6]. Chen, Y.N., “Flow-Induced Vibration and Noise in Tube-Bank Heat Exchangers Due to von Karman Streets” *Transactions of the ASME*, February, 1968.

[7-7]. Courtesy CMI.

[7-8]. Garud, Y.S., S.R. Paterson, R.B. Dooley, J. Hickling and A. Bursik, *Corrosion Fatigue of Water-Touched Pressure Retaining Components in Power Plants*, EPRI, Palo Alto, CA, TR-106696, November 1997.

8

DESIGN: INSTRUMENTATION AND CONTROLS

8.1 Overview of this Chapter

Proper instrumentation and controls are essential for efficient operation, as well as for reducing damage and preventing failures and maximizing availability. This Chapter addresses both cycle chemistry monitoring as well as control of the combustion and steam turbines during startup and shutdown cycles.

8.2 Design of Cycle Chemistry Monitoring and Instrumentation Systems

Action 8.2 *Design the required cycle chemistry instrumentation system based on the need to monitor key parameters.*

Rationale: *Will aid in the optimization of feedwater (or pre-HRSG or pre-deaerator) and HRSG treatments, will enable feedback to help minimize corrodant ingress and concentration, and help reduce corrosion product generation and transport.*

Potential HRSG Damage: *All waterside (internal) corrosion mechanisms.*

8.2.1 Introduction

The design process should result in the inclusion of a rapid response cycle chemistry monitoring system with approach response controls for the specific needs of the unit. The optimal system should consider the anticipated staffing, and the experience of the operators of the unit. Instrumentation and controls for water chemistry are integral to reliable operation of combined cycle units with HRSG. Unfortunately, there are too many experiences in the procurement, design and construction of combined cycle units where this aspect of the chemistry program does not receive the attention it deserves. It often follows that problems, which otherwise would have been readily identified and corrected, become issues of concern during the commissioning and early operation of these units.

The following requirements are important for cycle chemistry monitoring in HRSG units:

- High reliability yet affordable instrumentation is a top priority.
- Analyzers that minimize staff involvement are generally preferred; thus, auto-calibration features are considered desirable, while instruments requiring manual calibration are viewed as less attractive.

Design: Instrumentation and Controls

- Linking of on-line analyzers to plant data management systems to allow access by the control room operators as well as to permit access by personnel not at the plant is viewed as essential.
- Instrument quality assurance and quality control (QA/QC) is regarded as very important; plant operators desire instrumentation featuring automated QA/QC capabilities to minimize reliance on the staff to provide this function.
- Linking the instruments to an expert system capable of assisting operators in responding to chemistry excursions is an important tool required to manage the chemistry in a way that maximizes unit reliability, and should be “designed in” for each unit.

This subsection focuses on the best practices EPRI has determined and reported on in *Interim Cycle Chemistry Guidelines for Combined Cycle Heat Recovery Steam Generators (HRSGs)* [8-1].

8.2.2 Cycle Chemistry Parameters to be Monitored

The choice of parameters to be monitored will depend on the type of control chosen, key aspects of makeup water purity, and the host of other issues described in previous sections. A listing of “core” cycle chemistry monitoring parameters and monitoring points is provided in Table 8-1. The “core” parameters are considered the minimum level of surveillance that is needed for all HRSG units.

Table 8-1
“Core” HRSG Cycle Chemistry Monitoring Parameters
(Minimum Surveillance for Most Units)

Parameter/Monitoring Approach	Monitoring Points
Cation Conductivity Continuous by On-Line Analyzer	• Condensate Pump Discharge • Condensate Polisher Effluent • Feedwater (or Economizer Inlet) • Blowdown or Downcomer • Saturated Steam, and Main or Hot Reheat Steam
Specific Conductivity Continuous by On-Line Analyzer	• Treated Makeup • Condensate Polisher Effluent (OT) • Blowdown or Downcomer (PT, EPT and CT)
pH Continuous On-Line Analyzer	• Blowdown or Downcomer (Drum Units)
Dissolved Oxygen Continuous by On-Line Analyzer (May Be Shared)	• Condensate Pump Discharge • Feedwater (or Economizer Inlet)
Sodium Continuous by On-Line Analyzer	• Main or Hot Reheat Steam
Phosphate Grab Sample Analysis Each Shift (Or Continuous by On-Line Analyzer)	• Blowdown or Downcomer (PT and EPT)
Silica Grab Sample Analysis Each Shift (Or Continuous by On-Line Analyzer)	• Treated Makeup

The listing of “Suggested Additional Monitoring or Diagnostic Parameters” indicated in Table 8-2 represents those chemistry surveillance measures most likely to be included in customized chemistry programs for specific plants and units. Still other chemistry parameters that may be monitored under special circumstances include the following:

- Ammonia in Feedwater—to improve control of feedwater treatment or to optimize the treatment approach.
- Copper in Feedwater—to evaluate feedwater treatment in HRSG units with copper alloys (HRSG/combined cycles usually have copper-free feedwater systems, but may have copper alloys in the condenser.)
- Sulfate and Chloride in Treated Makeup, Condensate, Condensate Polisher Effluent and Steam—to evaluate cycle contamination and transport involving these species.
- Sodium in Treated Makeup—to evaluate demineralizer performance.
- Total Organic Carbon (TOC) in Feedwater, Boiler Water and Steam—to assess the effect of organic based proprietary treatments and makeup contamination on cycle chemistry

Design: Instrumentation and Controls

Table 8-2
Suggested Additional Monitoring, Troubleshooting or Diagnostic Parameters

Parameter/Monitoring Approach	Monitoring Points
Specific Conductivity Continuous by On-Line Analyzer	• Feedwater (Economizer Inlet)
pH Continuous by On-Line Analyzer	• Feedwater (Economizer Inlet)
Sodium Continuous by On-Line Analyzer (May Be Shared)	• Condensate Pump Discharge • Condensate Polisher Outlet • Blowdown or Downcomer (PT, EPT and CT) • Saturated Steam
Silica Grab Sample Analysis Daily	• Blowdown or Downcomer • Saturated Steam
Chloride—Grab Sample Analysis Daily	• Blowdown or Downcomer (EPT, CT, AVT and OT)
Sodium Hydroxide Grab Sample Analysis Daily (Or Derived from Conductivity Data)	• Blowdown or Downcomer (CT)
Hydrazine Grab Sample Analysis Each Shift (Or Continuous by On-Line Analyzer)	• Feedwater (Economizer Inlet)
Iron Grab Sample Analysis Weekly	• Feedwater (Economizer Inlet)
ORP (recommended for cycles which will use reducing treatment AVT (R) – essentially only those that include copper alloys in the feedwater). Continuous by On-Line Analyzer (when used)	• Feedwater (Economizer Inlet)
Total Organic Carbon Grab Sample Analysis Weekly	• Treated Makeup • Condensate Pump Discharge
Air Inleakage Check Air Removal Rate Daily	• Condenser Air Removal System

In general, it is neither practical nor necessary to routinely monitor all species of interest in the boiler water. It is suggested that the primary control of combined cycle/HRSG chemistry is through cation conductivity. Control curves are available which indicate maximum permissible values as a function of drum pressure for the various treatment approaches [8-1].

8.2.3 Sampling and Analyzers

In general, the use of on-line analyzers for continuous analysis of chemistry is preferred. However, some provision is made for use of shared instrumentation (dissolved oxygen) and laboratory analysis of grab samples (silica and phosphate). The monitoring approaches suggested recognize limitations on manpower at many HRSG plants and the fact that some analyzers require significant maintenance attention to perform reliably.

Analyzers suitable for low level analysis of anions and organics are not expected to be included in an HRSG plant laboratory. Such testing would need to be contracted to an outside laboratory with an ion chromatograph (for anions) and a TOC analyzer (for organics).

Desirable compatibilities and features of a sampling system have been established, as shown in Table 8-3 [8-1]. As included in Table 8-3, isokinetic sampling is recommended and is especially important when monitoring iron, copper and other metals in the steam/water cycle. Failure to maintain isokinetic conditions introduces bias, since suspended solids (and moisture in saturated steam) will not be collected in quantities consistent with their levels at the sample source.

Table 8-3
Summary of Criteria for Sampling

Sample	Criteria
Pressurized condensate and feedwater with representative sampling of particulates	• Isokinetic sampling velocity • Velocity of 1.5 - 1.8 m/sec (5 - 6 ft/sec) • Primary sample cooler at sample source • Isokinetic sampling probe
Boiler water from blowdown lines or circulation pump manifold	• Velocity of 1.5 - 1.8 m/sec (5 - 6 ft/sec) • Primary sample cooler at sample source
Boiler water from a downcomer or other pipeline	• Isokinetic sampling velocity • Velocity of 1.5 - 1.8 m/sec (5 - 6 ft/sec) if consistent with isokinetic requirements • Primary sample cooler at sample source • Isokinetic sampling probe
Saturated steam from steam leads From larger diameter lines From dry pan sampler	• Isokinetic sampling velocity • EPRI single port nozzle located 0.75 to 2 steam lead diameters from the steam lead inlet • Sufficient nozzles should be used to provide sampling of a representative fraction of all steam leads along the drum • Primary sample cooler at sample source • Isokinetic sampling probe • Velocity of 1.5 - 1.8 m/sec (5 - 6 ft/sec)
Superheated steam	• Isokinetic EPRI probe • Primary sample cooler at sample source
Condensate at subatmospheric pressure	• Velocity of 1.2 – 1.5 m/sec (4 - 5 ft/sec) • Large diameter sample nozzles net positive suction head actual (NPSHA), greater than net positive suction head required (NPSHR) at all conditions

8.3 Chemical Feed Systems and Controls

As with the water chemistry analyzers, the equipment selected to add chemicals to the HRSG cycle must be designed with the needs of the individual unit in mind. In order to ensure effective treatment of the cycle and help to minimize the potential for chemistry related HRSG tube failures the following aspects of chemical feed equipment and control systems must be addressed during unit design:

- **Plant Staffing.** Availability of personnel to operate and maintain this equipment must be considered carefully. In most instances, approaches that minimize personnel time requirements, such as those that allow for quick connect and disconnect of liquid chemicals in bulk solution, will be more favorable than those that require handling and dilution by plant staff (and also increase the risk of chemical exposure).
- **Feed System Capacity.** Feed system sizing should encompass all operating conditions and requirements including system fill, unit startup, minimum and maximum load operation, and conditioning for wet layup.
- **Chemical Feed Controls.** Properly selected and designed automatic control systems for feedwater treatment chemicals will always provide better performance than manual feed control or improperly configured automated controls. For pH control treatments (ammonia or amines) automated control based on feedwater flow and specific conductivity works very well. For hydrazine and other reducing agents (where needed, see Chapter 5), automatic control based on the feedwater flow and ORP reading is considered best practice. For solids based boiler water treatments (phosphate and caustic), manual control based on changes in the boiler water pH and other cycle chemistry conditions should be practiced. The feed systems for these chemicals should allow for rapid operator response to chemical excursions indicated by the on-line analyzers.

Further, feedwater and boiler water chemical treatment addition points must be selected in a manner with the overall cycle design as well as the arrangement and treatment requirements of the individual HRSG circuits.

8.4 Combined Cycle Unit Integrated Modulating and Sequence Controls

Action 8.4a Automate startup and shutdown procedures and limit CT ramp rates to the more restrictive of either the HRSG or the ST.

Action 8.4b Provide the HP and HRH bypass valves and ST HP and IP inlet control valves with a demand HP saturation temperature characteristic comprising ramp rates and holds that is acceptable to the HP steam drum.

Action 8.4c Automate the sequenced opening and closing of HP superheater and reheater drains, pipe drains, vents, etc., during coordinated startup.

Action 8.4d Automate the cooling of HP superheaters during normal shutdowns by providing a signal from the DCS to the CT controls to ramp down the CT exhaust gas temperature and hold at minimum load before the CT is released for final shutdown.

Action 8.4e *Consider the addition of replaceable temperature measuring probes for the HP superheater header and HP steam drum to permit increased ramp rates.*

Rationale: *Fatigue damage in HRSG components such as HP superheater headers and the HP drum are very strongly influenced by step changes and ramp rates in the temperature of their internal fluids. Appropriate control systems and algorithms can improve unit startup and shutdown without excessive damage to critical parts of the HRSG.*

Potential HRSG damage: *Creep fatigue, thermal fatigue, possibly corrosion fatigue.*

The rate of cyclic life expenditure in HRSG superheater headers is substantially impacted by the rate of change in steam temperature during startups and shutdowns (see discussions in Sections 4.5 and 7.5).

Throughout operation, the CCGU is controlled through the Distributed Control System (DCS). The DCS receives input signals of plant conditions, incorporates control algorithms for the various modulating controls, and outputs demand signals to the plant controllers. The DCS also interfaces with the CT and steam turbine control systems.

The plant controllers for the main power train, comprising one or more CT/HRSG trains and an ST, can be modulated either by the operator through the interface with the DCS, or automatically by the DCS. During normal on-load operation, between about 50% and baseload, the power trains of all F-class and equivalent CCGUs are controlled substantially, or entirely automatically, by the DCS. Thus, during operation over its normal load range, operation of the power train is automatic and the unit operator's role is limited to (i) selecting the desired CT output, (ii) observing the condition of the plant and (iii) being prepared to take over manual control of one or more of the control loops following a major CCGU transient or when a control loop develops a fault. Manual control is relinquished when plant conditions have stabilized and/or the control loop fault has been repaired.

There are substantial benefits to be obtained by automating the control of CT exhaust gas temperature and thereby HP and HRH steam temperatures and also the HP and HRH pressures during startup. This is particularly true on units intended for some periods of cycling service. Most of the fatigue-related damage accumulated by the critical components of HRSGs and STs occurs during startup and shutdown of CT/HRSGs, and not during normal on-load operation. Automation improves startup reliability by simplifying startups and establishing a high degree of repeatability in conditions imposed on all components. Even more significantly, automation preserves the medium-to-longterm durability of those critical parts of the HRSG that are especially vulnerable to fatigue-related damage by preventing excessively rapid startup ramps.

On most F-class and equivalent CCGUs, during startups, the ST OEM usually provides stringent specification of the steam conditions to be provided before roll-off of the ST and the subsequent maximum rate of increase in steam temperature or enthalpy at the HP and IP inlets to the ST. Some installations go further, and interface the CT and ST control systems through the DCS and automate the rate of loading of the CT during startups with cold or warm ST rotor temperatures. This is done by arranging the CT combustion controls to provide a gas exhaust temperature characteristic so that HP and HRH steam conditions match the critical ST metal temperature.

A small number of F-class CCGUs designed for extensive cycling have operated successfully with CT exhaust gas temperature matching. This provides a CT exhaust gas temperature demand signal from the DCS that adopts whichever of the HRSG or ST has the more restrictive ramp rate as determined by the DCS. The determination is typically made from the initial ST metal temperature and HP drum saturation temperature; the temperature to which the HP superheaters cool during the shutdown period. Such units are routinely started by a single operator command. Input is made to the HP and HRH bypass valve and/or ST inlet valve controller set points, and also to the CT when holds are required for heat soaking, by the DCS. The DCS and CT controls run up and load the CT to a pre-selected target with appropriate hold points and with appropriate CT exhaust gas temperature ramps. The objectives are to maintain dynamic HP steam pressures and temperature conditions acceptable to the ST, and to the HRSG superheater headers and HP steam drum.

A significant obstacle that has thwarted more widespread use of CT exhaust gas temperature matching and automated control of steam pressures and temperatures by the DCS during every startup and shutdown has been the lack of specification by the HRSG vendor of limits for HP steam temperature ramp rates. As indicated in Section 7.4, HP superheater headers thicker than about 25 mm (1 inch) are vulnerable to potentially severe creep fatigue damage unless the HP steam temperature is closely controlled to a ramp rate that is compatible with the design lifetime starts for the thickness of the HP superheater headers.

It is recommended that the HP steam temperature and pressure characteristics developed during each startup be controlled automatically by the DCS using two sets of algorithms. One set of algorithms (i) calculates the acceptable ramp rates and hold points for the HP steam temperature based on the initial HP drum saturation temperature, (ii) compares the computed rate acceptable to the HRSG with similar calculations for dynamic steam temperatures acceptable to the ST, and (iii) takes the more restrictive of the HRSG and ST allowable heating rates. These steps result in a demand signal for target CT exhaust gas temperature until the CT/HRSG reaches its target load above 50% of CT output.

The second algorithm in the DCS calculates the HP pressure characteristic from the initial HP drum pressure, generating holds and ramp rates for the HP saturation temperature. This is then used to continuously modulate the HP and HRH steam pressures through each startup, and provides an initial hold pressure and demand signals to the HP and HRH bypass valves and to the ST HP and IP inlet valves throughout the startup.

It may be possible to accelerate HP steam temperature and pressure ramp rates when heat transfer rates are lower and develop a more linear through-wall temperature gradient in the header wall. Control invoking this type of feedback may be accomplished by installing thermocouples at the outer surface and midwall of the HP superheater outlet header and HP steam drum, along with permanent thermocouples at a few tubes close to their attachment to the HP superheater outlet header. By measuring the thermal gradient through the header wall, in conjunction with results from sophisticated thermal-mechanical analysis of the HP superheater outlet header, algorithms can be developed that permit the DCS to accelerate the steam temperature ramp rates, when the measured thermal gradients permit, without increasing the thermal stress above a critical value.

8.5 References

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9

FABRICATION AND CONSTRUCTION ISSUES

9.1 Overview of this Chapter

The preceding Chapters 4 through 8 have dealt with design-related aspects of achieving reliable HRSGs before they are built and enter service. This chapter and the following chapter on commissioning turn to the proper implementation of the goals and actions developed during the design phase. Specifically, this chapter addresses several HRSG fabrication and construction topics, which have been found to have a significant impact on reliability once a HRSG enters service.

Specific issues include:

- transport and storage of HRSG components prior to installation
- field erection of piping
- proper execution of welded construction when using modified 9% chromium materials
- preoperational cleaning
- testing of pressure parts
- installation of cycle chemistry monitoring equipment

9.2 Transport and Storage

Action 9.2 Establish and execute appropriate procedures to ensure adequate protection of HRSG components during transportation to the site and storage at the site during construction.

Rationale: Prevent accumulation of contaminants in the cycle; prevent corrosion of pressure part surfaces; prevent accumulation of debris in pressure parts that could lead to tube blockages on startup.

Potential HRSG Damage: Corrosive processes to internal and external tube/header surfaces; excessive deposition caused by contaminants accumulating in circuits; debris remnant in pressure parts can lead to blockages and short term overheating.

The reliability and performance of HRSGs is strongly dependent on the condition of pressure part components and their exposure to potentially damaging conditions from the time they leave the shop until the time they are installed. As such, the transportation and shipment of components is

every bit as critical as the other aspects of a successful HRSG installation. The following checklist provides some key considerations pertaining to transport and storage:

- The interior of all equipment should be free from all foreign material such as welding rods, waste, loose mill scale, oil, grease, or other deleterious material. All openings should be closed immediately after cleaning. Rust, if any, should consist of no more than a surface film discoloration that can be readily removed by wiping.
- The sections that have been hydrostatically tested in the shop should be drained of all water prior to crating and shipment. If there is any doubt whether a vessel containing any water and the parts will be shipped or stored where freezing could occur, a suitable antifreeze should be used to prevent component damage.
- The equipment should be suitably crated, boxed, or otherwise prepared for shipment to prevent damage during handling and shipment. Each box, crate, or component should be marked on the outside with the shipping weight.
- Austenitic stainless steel pressure part materials should be protected during storage, handling and shipment from seawater, seawater spray, road, and rain or dew when subject to industrial atmospheres.
- All flange faces, machined surfaces such as tube and header beveled ends and threads should be clean and coated with a corrosion preventative. Flange faces, couplings, threads and machined surfaces should be protected with suitable covers or plugs made of wood, metal, or plastic. Exposed finished and machined surfaces, including bolting, should be given a heavy coating of rust inhibiting compound. Bolt threads should be protected from damage.
- The storage and handling of materials should prevent damage prior to application or installation. Protection should include:
 - Pressure part openings should be sealed to prevent entry of moisture.
 - Pressure parts should not be stored in direct contact with the soil.
 - Austenitic pressure parts should not be supported on porous supports in contact with the soil.
 - Lined sections should be protected from water.
- Lifting devices and structural bracing should be provided to permit handling and lifting without damage during shipment and erection.
- Bracing and supports should be provided to prevent damage during shipment. Temporary steel shop attachments not required for field use should be removed prior to shipment. Temporary bracing and supports should be painted yellow to denote removal is required before operation.
- All equipment and assemblies should be cleaned inside and outside prior to shipment to remove grease, oil, weld spatter, scale, slag and foreign matter.
- All liquids used for cleaning or hydrostatic testing should be removed prior to shipment.
- Shop installed insulation should be protected against mechanical damage and degradation from adverse weather conditions and contamination from foreign materials which could pose a corrosion risk.

- Equipment to be stored indoors, and kept clean and dry at all times, including the items listed in Table 9-1.

Table 9-1**Examples of Equipment to be Stored Indoors and Kept Clean and Dry**

Burners and accessories	Igniters	Spare parts
Control panels	Motors - electric and air	Strainers
Control equipment - all types	Motor starters	Thermocouples
Damper drives and interconnecting linkwork	Pumps	Valves - all types
Drum internals	Refractory	Water columns and gages
Electrical devices - all types	Safety valves	Water level indicators
Heat insulation	Soot blowers	

9.3 Erection Issues for Piping Systems

Action 9.3 *Establish and execute appropriate procedures to ensure piping components are properly installed.*

Rationale: *Prevention of excessive stresses, limiting the accumulation of internal debris, optimizing the effectiveness of instrumentation.*

Potential HRSG Damage: *Stress- and fatigue-related damage, blockages.*

General guidance includes the following:

- Field piping should be assembled and installed in accordance with the applicable sections of ASME B31.1, or equivalent. Piping within the scope of steam generation should be assembled, installed and tested and inspected in accordance with the ASME Boiler and Pressure Vessel Code, or equivalent.
- The piping system should be supported, anchored and guided so that it should not be overstressed from any operating condition and should not react on equipment beyond limits established by manufacturers.
- All piping should be adequately supported, anchored, guided, or strutted to prevent undue vibration, deflection, stress or strain on any piping or equipment. Piping should be completely installed from origin to terminus before permanently anchoring.
- Special care should be taken that the installed piping is free and clear of all foreign materials, construction debris, etc.
- Installation and orientation of all gauge glasses, level controllers, thermometers, thermocouples, pressure gauges, etc., should be arranged for convenience of operation and ease of maintenance.

9.4 Proper Execution of Welded Construction When Using Modified 9% Chromium Materials

Action 9.4 Develop, qualify and carefully perform proper welding and heat treatment procedures when fabricating and erecting tubing/header components using modified 9% chromium materials.

Rationale: Proper execution of sound welds and avoidance of weld-related problems specific to modified 9% chromium materials.

Potential HRSG Damage: Weld-related cracking during fabrication/erection, in-service failures resulting from conditions introduced during welding.

The use of modified 9% chromium alloys (P91, T91, P92, T92) in HRSG high pressure superheaters has become very popular due to the increased allowable stress values of these materials. The use of P91, or equivalent, instead of P22 for superheater outlet headers and outlet manifold can minimize the required wall thickness and thus lower thermal stresses during temperature transients. In general the success of these alloys to date has been very good. However, there have been some early service life failures that have occurred in these materials. Problems have included excessively hard or soft weld/heat affected zone regions due to lack of proper post weld heat treatment, thermal shrinkage cracking, stress corrosion or hydrogen cracking, cold work-influenced cracking, erection load-induced cracking, and problems at material transitions. A summary of these issues, their most likely root cause(s) and potential solutions are presented in Table 9-2.

Table 9-2
Issues and Solutions Pertaining to Welding of Modified 9% Chromium Material

Potential Issue	Root Cause(s)	Possible Solutions
Excessive hardness (> 265 HV), and severe reduction in ductility	Lack of or insufficient post weld heat treatment (PWHT) (the as-welded hardness is typically > 400 HV) Failure to cool the weld below the martensite finish temperature prior to performing PWHT (the retained austenite will form hard, untempered martensite when the weld is cooled from the PWHT) Failure to qualify the PWHT or perform selected shop/field verification hardness tests	• Don't load the welds prior to PWHT. • Use a verified (qualified by testing), PWHT sequence that includes limits on the heating rate, hold time, and cooldown rate. A typical PWHT cycle is: Heat to 288°C to 315°C (550°F to 600°F) and hold for 2 hours (hydrogen bakeout), cool at 167°C/hr (300°F/hr) to 80°C to 93°C (175°F to 200°F), heat at 110°C/hr (200°F/hr), hold for 1 hour/inch of thickness (based on thicker side of joint) at 745°C to 760°C (1375°F to 1400°F), cool to 635°C (1175°F) at 55°C/hr (100°F/hr), then cool to 425°C (800°F) at 110°C/hr (200°F/hr), then cool to ambient at 165°C/hr (300°F/hr). • Use furnace PWHT or insulated bands and resistance or induction heating (not oxyfuel heating) to ensure uniform heating. The heated region must extend well beyond both sides of the welds and should have a smoothly decaying temperature profile beyond the heated zone. The heated zone is typically $2.5(Rt)^{0.5}$ away from each side of the weld, where R is the inside radius and t is the wall thickness. The insulated zone is typically twice the heated zone. The temperature at the edge of the heated zone should be at least half of the temperature at the weld centerline • Thoroughly monitor the magnitude, rate of change, and distribution of PWHT temperatures. Good practice for pipe-to-pipe welds includes use of 8 thermocouples per weld: 4 equally spaced clock positions placed at locations approximately 6 to 25 mm ($\frac{1}{4}$ to 1 in.) from the edge of the weld. For tube welds, the number and location of thermocouples will depend on the number of tubes being simultaneously heat treated; enough thermocouples should be used to ensure that all the tubes are being uniformly heated. • Following PWHT, verify that the hardness is within the desired hardness range of 200 to 265 HV. The hardness readings should be made on a region that has been sanded to a 400 grit finish and readings should be made every 1.25 mm (0.05 in.) for 5 readings (6.35 mm (0.25 in.)) to either side of both weld interfaces. This hardness verification should be done using an acceptable sampling plan (one location for each pipe-to-pipe weld, some percentage of tube welds) • After hardness verification is complete, remove the hardness indentations and thermocouple attachment indentations by light grinding and sanding to a 400 grit finish. This step is recommended because creep cracks have initiated in this material from small surface defects that were not removed prior to service exposure.

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Table 9-2
Issues and Solutions Pertaining to Welding of Modified 9% Chromium Material (continued)

Potential Issue	Root Cause(s)	Possible Solutions
Excessive softening (< 200 HV) and inadequate stress rupture or creep-fatigue life	Excessive or uncontrolled PWHT temperature. The required minimum ultimate tensile strength of T91/P91 is 85 ksi, with a corresponding hardness of 182 HV. Hardness values below 200 HV have been associated with incidences of early service Type IV cracking.	• See the PWHT recommendation above, paying special attention to thorough monitoring and control of the PWHT temperatures. • If PWHT above 760 °C (1400 °F) is contemplated, perform full scale mockups of the weld joint in question to verify that the material's lower critical temperature is not exceeded (especially within the base metal heat affected zone). Keep in mind that the lower critical temperature is a function of alloy chemistry (i.e., high Ni plus Mn contents lead to low A_{c1} temperatures) and grain size (thus the focus on the base metal heat affected zone)
Thermal shrinkage cracking	Cooling a partially filled weld joint	• Maintain preheat/interpass temperature and don't interrupt the welding process until the weld joint is completed
Stress corrosion cracking or hydrogen cracking	Exposure to moisture of the weld joint or welding consumables prior to or during welding, or following welding but before the PWHT	• Purchase weld consumables with guaranteed low hydrogen levels • Use proper weld consumable storage (including GTAW/GMAW wires) • Don't weld on a wet, oily, contaminated weld joints. Don't weld in the rain without proper shelter. • Maintain weld preheat and interpass temperatures and include a hydrogen bakeout in the PWHT cycle (unless GTAW welding is used) • For thick or highly restrained joints, review the need for increased preheat temperatures or special weld joint designs and/or weld bead sequence, controlled arc energy procedures, etc. • Don't allow the welds to cool below the dew point during the "cooling below the martensite finish temperature" portion of the PWHT
Erection load-induced cracking	Placing excessive erection loads on the welds	• Maintain welding supports throughout the welding and PWHT • Do not lift or place loads on the welds until PWHT has been completed and the hardness has been verified
Cold work influenced cracking	Cold work, particularly if the strain is > 15%, followed by service aging or heating during PWHT or during erection activities	• Normalize and temper all components (e.g., bends, swages, etc.) following the working operation. Alternatively, perform a range of stress rupture tests on the post-formed components to demonstrate that they have adequate stress rupture properties without the need for the normalizing heat treatment • Do not bend or heat modified 9% chromium tubing during erection activities

Table 9-2
Issues and Solutions Pertaining to Welding of Modified 9% Chromium Material (continued)

Potential Issue	Root Cause(s)	Possible Solutions
Material transition influenced cracking (typically in welds connecting 9% chromium alloys to 2-1/4% chromium alloys). This may involve thickness transition issues or carbon denuded zones occurring at the side of the weld where the alloy transition occurs.	Excessive PWHT temperatures coupled with poor weld design, and/or excessive axial or bending loads	- For weld joints with thickness transitions, ensure that transitions have a 5:1 taper. Alternatively, demonstrate by local finite element (or other evaluations) that the design does not significantly elevate the stress during steady state or during temperature transients. - For tube-to-header connections, use weld consumables that match the tubing and design the weld configuration such that the weld interface on the header side of the connection is a low stress region (the use of nickel-based weld consumables or use of butter layers of nickel-based alloys at the alloy transition side of the weld are being considered). - Perform full size mockup welds to demonstrate that a carbon denuded zone is not formed during the upper end of the specified PWHT temperature range. Alternatively, design the weld connection or global tube/pipe/support system so that the weld interface with the carbon denuded zone doesn't need high stress rupture properties. A good check is to assume this interface has stress rupture properties equivalent to 1-1/4 Cr- 1/2Mo steel and verify that it has adequate stress rupture life.

9.5 Preoperational Cleaning

Action 9.5a *Establish and execute appropriate procedures to ensure clean and passive surfaces of HRSG components prior to unit startup.*

Action 9.5b *Prior to initial operation, the water surfaces of the steam generator should be evaluated and cleaned by physical and/or chemical processes.*

Action 9.5c. *Prior to initial operations, procedures such as steam or air blowing (preceded by mechanical or chemical cleaning if mill scale is present) should be completed to remove any loose particles and foreign objects from steam tubing and piping.*

Rationale: *Prevent accumulation of contaminants in the cycle; prevent corrosion of pressure part surfaces; prevent accumulation of debris in pressure parts that could lead to tube blockages on startup or cause damage to the steam turbine.*

Potential HRSG Damage: *Corrosive processes to internal and external tube/header surfaces; excessive deposition caused by contaminants accumulating in circuits; debris remnants left within in pressure parts can lead to blockage and short term overheating.*

For reliable HRSG operation, it is essential that waterside surfaces be free of oil and grease, mill scale, and corrosion products. Further, it must be verified that the system is free of construction materials or other debris that would otherwise interfere with steam generation and/or allow HRSG tube failure mechanisms to become active. A majority of combined cycle installations are not simple. They are usually comprised of multiple multi-pressure circuits that are linked together on the steam side. As such, ensuring that all of the pressure parts are suitably clean pre-operationally is a challenging task and it is important. EPRI is developing guidelines for

chemical cleaning of HRSGs and other combined cycle unit components; a publication on this subject is scheduled for late 2003.

Actions taken during prior phases of the project, including system design, equipment procurement, component storage and transportation, and unit construction, all impact the cleanliness of the cycle and the extent of preoperational cleaning required.

The specific purposes of preoperational cleaning are to:

- Ensure that steam and waterside surfaces are clean and passive, thereby minimizing the risk of corrosion and deposition during the commissioning period and initial commercial service operation.
- Remove materials that could interfere with passage of steam and water in the cycle, thereby preventing tube failures caused by short term overheating damage.
- Eliminate any abrasive materials and debris that, if present, could cause erosion and/or foreign object damage in the steam turbine.
- Minimize the impact of water chemistry on unit startups conducted during the commissioning period.

In theory, it may be possible, with proper fabrication techniques, component storage practices, construction techniques, etc, to proceed with combined cycle unit commissioning without the need for any preoperational cleaning. In practice, however, at least some degree of cleaning is required in virtually every case. Unfortunately, contract specifications and schedule requirements, as they relate to cycle cleanliness, are generally not well defined. This leads to confusion over what is needed, how the work should be approached, and which parties bear responsibility for establishing an acceptable state of cleanliness.

It is essential to keep in mind that responsibility for cycle cleanliness rests with several parties and that the improper actions of any can increase the preoperational cleaning requirements. Any program intended to control cycle cleanliness prior to commissioning must include a means to evaluate and measure the degree of cleanliness. The construction schedule should provide opportunities for visual inspections of components such as the condenser and hotwell, the deaerating heater where provided, any external heaters in the unit, and the individual circuits comprising the HRSG. As a result of these inspections, provision can be made to physically remove any dirt, dust, debris and other foreign material present. Also, the condition of metal surfaces (passive or actively corroding) can be determined and an assessment of the presence or absence of mill scale and organic residues can be made.

9.5.1 Scope of Preoperational Cleaning

Preoperational cleaning requirements are unique to each unit and must be determined on a case-by-case basis. In large measure, the cleaning requirements must be determined by a thorough inspection of the HRSG and the condensate/feedwater and steam piping systems. Inspectors should check accessible water and steamside surfaces for signs of mill scale, loose and adherent corrosion products, present of dust, dirt, debris and foreign material, residual construction materials and media, oils, greases, coatings and other preservatives, etc.

Results of the internal inspections of the combined cycle unit are generally sufficient to determine the type and extent of cleaning required. The main cleaning approaches that need to be are listed in Table 9-3. Note that, in the case of chemical cleaning, solvent formulations are available to serve more than one purpose.

Table 9-3
Primary Pre Operational Cleaning Methods

Physical Cleaning

- Manual (vacuuming and/or by hand) removal of loose materials
- Water flushing and draining to displace solids

Chemical Cleaning

- Removal of organic preservatives (oils, greases, etc.)
- Removal of mill scale and iron oxides
- Passivation of metal surfaces

Steam Path Cleanliness

- Steam blowing
 - Hydroblasting or chemical cleaning (for mill scale, if present)
-

Physical cleaning should always be performed consistent with the needs of the cycle, as defined during internal inspections. Chemical cleaning requirements depend on findings of physical examination and requirements of the equipment supplier. Minimum requirements of the manufacturer should generally be followed. However, a more rigorous preoperational chemical cleaning approach (than that indicated by the manufacturer) should be undertaken if indicated by the inspection findings. Equipment supplier guidelines and criteria should never be used as a “justification” to eliminate field inspections. Steam or air blowing of the steam piping and tubing is mandated by steam turbine manufacturers.

Modern manufacturing methods offer opportunities to greatly reduce or eliminate the amount of mill scale present in new steam generators. However, if mill scale is present on the steam tubing and piping, a physical or chemical process should be employed to remove it prior to steam blowing or air blowing. Shotblasting has been used effectively for mill scale removal, however, experience has showed that it is often difficult to entirely remove the media from the system after cleaning. More recently, hydroblasting techniques have been employed to help clean mill scale from steam tubing and piping. Typically, this is done as an initial cleaning step, which may reduce the extent of steam or air blowing needed to complete cleanup of the steam path. Chemical cleaning methods are also effective in mill scale removal, however, the costs associated with these methods and concerns over the wastes produced have resulted in consideration of mechanical removal methods, such as hydroblasting, in some cases.

In defining preoperational chemical cleaning requirements for the evaporator circuits of the HRSG, the need to apply solvents for removal of iron and mill scale frequently comes into question, especially since projects are often structured to eliminate the need for iron removal;

however, these approaches are not successful in all cases [9-1]. With respect to longterm HRSG dependability, it is generally best to take a conservative approach, as indicated in the following:

- All once-through evaporator circuits should receive preoperational chemical cleaning to remove iron.
- Drum-type evaporator circuits operating at or above 10.3 MPa (1500 psig) should receive preoperational chemical cleaning to remove iron unless extensive visual and fiber optics examinations of the drums, headers and tubing, supplemented by examination of representative samples from the tube bank indicate clean, passive, and corrosion-free surfaces clearly demonstrate that application of an iron removal solvent would be of no benefit.

9.5.2 Overall Project and Preoperational Cleaning Schedules

The project work schedule should be structured to accommodate internal inspections and the level of cleaning required. Flexibility is needed since the actual cleaning requirements cannot be determined until construction is essentially complete. Establishing an overall schedule that is realistic will allow for this, and if findings are favorable, the opportunity exists to do a satisfactory cleaning and complete the work on or ahead of schedule.

In establishing specific preoperational cleaning schedules, which may be developed for one or more units, it is very important to integrate performance of the work into the overall project schedule, in a way that minimizes cost impacts. For example, if cleaning of multiple combined cycle units is contemplated, the individual project schedule for each unit must be considered. Also, impacts on any system supply obligations that may exist must be taken into account; this is especially important when the project involves repowering of existing fossil units [9-1].

Schedules should also have some provision to allow re-inspection of the system following chemical cleaning. In general, the time and cost of making these inspections is very minor compared to the savings that will be realized by delivering a high dependability HRSG to commissioning and commercial operation. With proper planning and execution of the cleaning procedure, it is very unlikely that repeat cleaning will be required. On the other hand, it is quite possible that the need for further physical cleaning activity to remove any loose solids, foreign objects and debris present will be indicated.

9.5.3 Resource Requirements

Performance of preoperational chemical cleaning requires provision of several critical resources. These include:

- Sufficient work space to spot equipment used during cleaning and with proximity to the equipment to be cleaned.
- Demineralized water (and a means to transfer it to the work space).
- Supplies of power, service water and compressed air.
- Site labor and supervision.

Allocation of these resources must be sufficient to support the cleaning work as well as on additional construction commissioning or O&M activities ongoing elsewhere within the plant site.

9.5.4 Solvent Selection, Process Conditions and Development of Cleaning Procedures

These activities are clearly dependent on conditions noted during inspection of the unit to be cleaned and unit design factors, as discussed earlier. In addition, they will be influenced by waste disposal considerations and overall cost.

In cases where only removal of oil and grease and other organics (commonly referred to as “degreasing”) is required, the HRSG may be cleaned with either a phosphate solution (typically trisodium phosphate), with surfactants, or with a solvent containing both phosphate and surfactants.

For iron removal, either organic or inorganic cleaning solvents may be considered. In North America, preoperational cleaning with a chelant such as EDTA or citrate compounds is typically practiced; these solvents are also used in other countries. By including a suitable surfactant in the cleaning solvent, it is usually possible to effect degreasing, iron removal and passivation of metal surfaces with a single cleaning solvent.

Potentially applicable inorganic solvents for iron removal include hydrochloric acid (HCl) and hydrofluoric acid (HF). While HCl is widely used for operational cleaning of conventional boilers in North America [9-2], it has not been widely considered as a cleaning solvent for HRSG. By contrast, HF is commonly used to preoperationally clean conventional boilers and HRSG outside of North America. When inorganic solvents are used for iron removal, it is necessary to employ separate chemical solutions for organics removal, and neutralization and passivation of equipment. Also, more extensive rinsing is generally required with the inorganic iron solvents.

Development of unit specific preoperational cleaning procedures must consider the level of cleanliness, physical constraints imposed by the design, and the selected solvent and its required application conditions. To do this properly often requires input from the equipment supplier, system designer and chemical cleaning specialist. Issues that must be considered during the planning stage include:

- Definition of solvent flow paths.
- Temporary piping requirements.
- Specification of external pumps to be used for solvent addition, solvent movement and solvent removal.
- Specification of heat exchangers to allow attainment of suitable solvent temperature.

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- Identification of solvent “deadlegs” that will require special consideration during the cleaning procedure.
- Identification of existing and temporary valves that will be used to establish desired solvent flow paths.

In evaluating solvent flow requirements, it must be recognized that the normal or design flow path may not support effective chemical cleaning. To address this concern it may be necessary to either effect moderation of the system or use temporary piping and valves to establish more suitable flow paths. Depending on system arrangement and HRSG design, it is often not possible, for instance to perform an alkaline flush of the feedwater piping and water touched HRSG circuits in a single procedure. The ability or inability to isolate parts of the system needing cleaning is also a factor, which must be addressed when planning the work. Preparation of detailed procedures for cleaning requires time and should be done in parallel with construction of the unit.

9.5.5 Safety Issues

While safety is of paramount importance at every construction site, the safety issues related to chemical cleaning are unique and deserve separate consideration. Key elements of safety during preoperational cleaning include:

- Hydrostatic testing and, if necessary, repair of all equipment and temporary piping intended to handle chemical solvents, wastes and rinse solutions during the cleaning process (also see Section 9.7).
- Provision of safety showers and eyewash stations, supplying temporary equipment as needed if the permanent equipment is unavailable or not available in the work area.
- Provision of personal protective equipment for personnel providing labor and supervision in support of the work.
- Familiarity with site safety procedures and evacuation plans.
- Restriction of access to the equipment being cleaned by personnel not involved in the work.
- Prohibition on work activities such as welding, burning and grinding that are unsafe when cleaning solvents are in use.
- Establishment of solvent leak and spill containment procedures.

The safety plans and procedures established will also be generally applicable to operational chemical cleaning procedures.

9.5.6 Waste Management

Chemical cleaning solvent and rinse solutions require various levels of treatment and disposal, depending on the composition of the waste and the requirements of the environmental agency responsible for waste management practices in the jurisdiction in which the unit is located. The initial issue of concern is to provide adequate waste storage capacity and a means to transfer

waste from the unit to the storage area. A safety factor of at least 1.5 times the expected waste volume should be assumed to allow for contingencies such as solvent leaks from the system and additional flushing and rinsing. At many locations on-site storage of wastes now requires that containments be installed around each storage unit. It is also necessary to evaluate options with respect to onsite treatment and disposal of the waste solvent and rinse water. Costs of these options can then be compared to the costs of transport of the waste to a licensed treatment facility. At units with multiple units, there may be opportunities to reuse rinse water. Also, in some instances, it may be feasible to arrange for discharge of rinse solutions to publicly owned and operated waste treatment facilities.

9.5.7 Removal of Loose Particles from Steam Tubing and Piping

Removal of loose particulates from the steam tubing and piping is typically the final major task in construction of a unit. Once completed it is possible to proceed with unit commissioning and startup activities. Because of the risk of damage that these particles pose to the steam turbine, the equipment manufacturer mandates that steps be taken to remove solids from the steam path prior to placing the turbine in service. Traditionally, steam blowing to targets and observing the particles captured is practiced to verify removal of these particles from the superheater, reheater and main steam piping. The original steam blow technique created extremely high noise levels, however, there are now devices and procedures to appreciably reduce noise levels during steam blows.

Tests conducted with conventional boilers have shown that steam blows are ineffective in removing adherent deposits. In conventional designs, the boiler is operated to produce the steam required. This approach may be more difficult to follow with an HRSG due to the nature of its design. During steam blows, temperature and pressure transients are experienced in the evaporator tubing, superheater and reheater tubing, steam leads and blowoff piping. These transients impose stress, which may affect the fatigue life of these components. Air blowing and/or high velocity water flushes may be used in lieu of steam blowing. In view of the fact that the HRSG may not be able to be operated to provide the steam, there is likely to be considerable interest in alternative approaches to steam blowing for removing particulate material from the steam path tubing and piping.

It has been demonstrated that, in conventional boilers, potential problems created by steam blowing can be overcome by air blowing [9-2, 9-3]. Also, air blowing is sometimes less time consuming and less expensive than steam blowing, as well as being a safer and easier to perform procedure. Regardless of whether steam blowing, air blowing or water flushing is used, detailed instructions must be incorporated into the procedures for a successful blow. The HRSG and turbine manufacturer should be consulted for assistance in developing the procedures.

9.6 Testing of Pressure Parts

Action 9.6 Establish and execute appropriate procedures for nondestructive testing and hydrostatic testing for tubing, piping and valves.

Rationale: Confirmation of proper fabrication and construction.

Potential HRSG Damage: Nearly all damage mechanisms.

Appropriate procedures include:

- Nondestructive examination procedures should be in accordance with the applicable Code, specifications and the requirements therein.
- Tube bundles should be shop hydrotested. The test should be in accordance with the applicable Code and as follows:
 - All air should be vented from assemblies. Test pressure should be held for sufficient time to examine the entire assembly for defects, but not less than one hour.
 - Water for shop hydrotest should be potable. For ferritic materials the chloride content should not exceed 200 ppm and the water temperature should not be less than 21°C (70°F). The chloride content of water used for testing austenitic materials with more than 11% chrome should not exceed 50 ppm unless treated with an inhibitor of 1.5% soda ash and 0.5% sodium nitrate. The chloride content of the soda ash should not exceed 500 ppm. Hydrotest water quality documentation should be available.
 - Hydrotest water should be drained to the extent practical after hydrotest.
 - The hydrotest should be successfully repeated after any repairs.
 - If shipped to region where freezing can occur, suitable ‘antifreeze’ should be added to the section to mix with any remaining water to prevent freezing.
- Qualified personnel should check shop fabrications for both material specifications and dimensional accuracy.
- The date, test condition, and results of all required tests should be recorded and certified.
- Care should be exercised to protect vessels, equipment, and instrumentation, which can be damaged during piping systems pressure testing through the use of slip blinds or other suitable means.

Inspection and testing of piping should be performed in accordance with the requirements of the applicable code. Inspection and testing practices should follow the guidelines in Table 9-4.

Table 9-4
Test Methods for Piping Systems

Systems	Test Method
Fuel gas, compressed air, compressed gas, lube oil, control oil, fuel oil, concentrated chemical systems	Pneumatic (air/nitrogen) test at 1.2 times design pressure (special safety procedures apply)
All instrument tubing, vents, drains, water system designs with conditions not more than 1.04 MPa (150 psig) and 815°C (1500°F), piping between isolation valves and equipment connections, temporary piping systems, control oil, compressed air, lube oil, and all piping for which valving or blanking is not practical (piping terminal flanges should not be separated for testing)	Initial Service Test only---no hydrostatic or pneumatic test
Circulating water	Testable joints: low pressure pneumatic verification; welded joints: internal visual inspection only; other joints: hydrostatic test at 1.3 times design pressure; above grade: initial service test
All other systems and situations	Water hydrostatic test at 1.5 times design pressure with clean water at not more than 38°C (100°F) (water chemically treated as required); in no case to exceed limitations of ANSI/ASME B 31.1 Section 137.

Note: The test pressure should never exceed the maximum allowable test pressure of *any* non-isolated component in the affected system (pumps, valves, vessels, etc.).

Pressure testing of piping systems including hydrostatic, pneumatic, or initial service testing should be performed on systems following completion of erection.

- Valves should be given hydrostatic shell and seat tightness tests at the manufacturer's shop in accordance with MSS-SP61 (Manufacturers Standardization Society of the Valve and Fittings Industry, Inc.), ASME/ANSI B16.34, or equivalent, as applicable. Gate valves should be proven for tight shutoff in both directions.
- Valves should be tested for back seating tightness to demonstrate that they may be repacked under full working pressure.

9.7 Installation of Cycle Chemistry Monitoring Equipment

Action 9.7: *Ensure that the requisite chemistry monitoring features are installed during the fabrication and construction process so that the system is able to support chemistry commissioning activities.*

Rationale: *Prevent operation of the HRSG in a chemical environment that will enable deposition and corrosion activity to develop.*

Potential HRSG Damage: *Corrosion damage, particularly to tubing in evaporator, superheater and reheater circuits. Overheating damage to evaporator tubing may also be experienced. Damage can begin to develop during the commissioning period if chemistry monitoring capabilities are not established properly during fabrication and construction of the unit.*

Installation of the cycle chemistry monitoring equipment (as well as the sample lines, sample conditioning systems, grab sample systems, laboratory testing facilities, and links to other systems and equipment) is a vital part of the construction process. This equipment and the related systems must be operational during the commissioning and period and all subsequent commercial operations. Information on chemistry monitoring capabilities is included in Section 8.2 while cycle chemistry commissioning is presented in Section 10.6 of this report.

9.8 References

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- [9-2]. R. Bartholomew, D. Cline, E. Hull, K. Shields, J. Siegmund and S. Yorgiadis, *Guidelines For Chemical Cleaning of Conventional Fossil Plant Equipment*, 1003994, EPRI, Palo Alto, CA, November 2001.
- [9-3]. J. F. Conway, R. E. Craft, Jr. and A. Zarechnak. "Prevention of Solid Particle Erosion At Keystone Station.", *Solid Particle Erosion of Steam Turbine Components: 1985 Workshop*, CS-4683, EPRI, Palo Alto, CA, August 1986.

10

COMMISSIONING

10.1 Overview of this Chapter

There are a number of activities that need to be conducted in order to confirm the design life calculations for unit transients. EPRI will be addressing the whole commissioning area in a follow-on project. The guidance presented here is an overview of key considerations needed to follow-through on decisions made during the design phase. Key sections address: performing unit transient tests (Section 10.2), evaluating transient thermal conditions (Section 10.3), confirming drain and vent systems are working as designed (Section 10.4), fine tuning distributed control systems (Section 10.5), refining cycle chemistry controls during the commissioning stage (Section 10.6), and monitoring flue gas and other characteristics (Sections 10.7 and 10.8).

10.2 Performing Unit Transient Tests

Action 10.2a During commissioning, perform transient testing of all designed operating procedures to tune key control systems and establish the adequacy of auxiliary systems.

Action 10.2b Before commissioning commences, prepare a list of specific transient tests to be conducted.

Action 10.2c Be aware that significant thermally induced stresses can develop during commissioning testing itself and care needs to be taken to understand and avoid the most damaging transients.

Action 10.2d Install additional temporary thermocouples and instrumentation where needed.

Action 10.2e If excessive conditions are detected during transient testing, then seek mitigation through: (i) modifications to ramp rates, (ii) timing sequences of key events, (iii) analysis to determine the conservatism of “actual” values, and, lastly, (iv) design modifications to the hardware.

Rationale: Properly conducted commissioning tests will enable verification of key design life calculations for the full range of unit transients.

Potential HRSG Damage: Essentially all HRSG damage mechanisms are caused or exacerbated by cyclic stresses or changes to cycle chemistry caused by transient operation.

Commissioning

Many CCGUs are installed to very tight construction schedules that allow inadequate time for commissioning of the plant. In consequence, commissioning activities give priority to those activities most critical to establishing the CCGU on-load, completing the thermal performance tests and obtaining early provisional acceptance by the purchaser for commercial operation. Tuning of key control systems to ensure stable control of critical conditions during startups and when making large load changes is often neglected during commissioning. So too are tests to establish the adequacy of auxiliary systems used only during startups or upset conditions. CCGUs are sometimes accepted for commercial service before they have completed even basic commissioning, and often the performance of major transient tests is not included in the acceptance tests. This is imprudent, even for CCGUs that will operate continuously thereafter, and is unacceptable for CCGUs expected to immediately be available for cycling service.

Before hot commissioning commences, it is important to ensure that the plant is complete, including the DCS and DCS historian. Thus the purchaser should specify what must be complete before first fire and before the reliability run. The tests before provisional acceptance of the CCGU should include a specific list of transient tests that must successfully demonstrate that the CCGU performs in accordance with the design intent and expectation.

Transient tests should include, but not be limited to CT/HRSG and CCGU startup tests after specific shutdowns periods following normal shutdowns, including overnight shutdown periods, 30 hour shutdowns, 56 hour shutdowns and cold start from ambient temperatures. Each transient test should be performed in accordance with the operating procedures developed during design (see Section 4.3). Before performing these tests, additional temporary thermocouples and instrumentation should be installed to determine whether the conditions developed in the HRSG are compatible with those assumed for design verification calculations.

Where the conditions developed in critical parts of the HRSG during the startup tests exceed those assumed in design validation calculations, modifications to ramp rates and the timing sequence of key actions may improve conditions. If conditions continue to exceed those used for validation, the HRSG OEM may resort to more sophisticated analysis to permit conservatism in the original model to be reduced. If this is unsuccessful, practical design modifications to the hardware may be necessary.

10.3 Evaluating Thermal Transient Conditions

Action 10.3a Develop a list of potentially susceptible locations for confirmation of thermal transients; rank order by agreed upon criteria.

Action 10.3b Perform transient tests in accordance with operating procedures specified during the design phase – if automatic control was specified, tests should be run using automated DCS.

Rationale: To confirm levels of transient stresses developed in design phase.

Potential HRSG Damage: Primarily thermal fatigue and creep fatigue, however many HRSG damage types can be exacerbated by cyclic thermal stresses.

During commissioning, a series of startups (from cold, cool, warm and hot start conditions) and normal shutdowns must be performed to measure and capture the dynamic tube temperatures developed during each of these major transients. The HRSG design concepts and details that are conducive to the development of significant thermal stresses in tubes at attachments to the headers are discussed in depth in Chapter 7. These commissioning tests should be performed in strict accordance with unambiguous, precise, step-by-step written operating procedures developed during the design stage, as discussed in Section 4.3.

Where, as discussed in Section 8.4, the unit is designed to use the DCS to (i) automatically control the HP steam temperature and pressure ramps and holds during startups and shutdowns, and (ii) automate the timing of sequenced opening and closing of drains, vents, etc, during startups, the startup tests should be performed automatically without operator intervention, in accordance with the design intent.

The presence of damage susceptible design concepts and details in the HRSG should have been identified by the purchaser during the design stage. Key details should have been evaluated by agreeing with the OEM on appropriate analysis. Three alternative evaluation means are using: (i) conservative assumptions for maximum tube-to-tube temperature differences based on previous measurements from closely similar designs of HRSG, (ii) dynamic simulations to determine transient row-to-row temperature differences where there was no prior experience, or (iii) conservatively calculated thermal stresses. Expected stress levels should be compared to desired design life and the number of startup-shutdown cycles specified for the HRSG.

Before unit commissioning commences, the conclusions from the design verification process should be summarized in a panel-by-panel list of all susceptible locations in the HP superheaters and reheaters, evaporators, economizers and preheater, together with the anticipated or limiting tube-to-tube temperature differences assumed or calculated for each suspect location.

Based on experience from measurements of tube-to-tube temperature differences in other designs of HRSG, the purchaser should rank the damage susceptible locations. Ranking criteria may include factors such as (i) the level of confidence in the tube-to-tube temperature difference assumed by the OEM for design verification analysis, (ii) the level of conservatism in the analytical model used to predict cycles to failure, and (iii) the margin between predicted cycles to failure and the design number of startups. When selecting those locations to be investigated, additional importance should be given to those locations where the magnitude of the tube-to-tube temperature difference is significantly influenced by the rate of heating or cooling during startups or shutdowns, or by the timing of opening and closing of drains, vents, bypasses, feedwater valves, etc. Sample locations include:

- For reasons discussed in Chapter 7, HP superheater and reheater tube rows are always strong candidates for thermocouple installation. Thermocouples should be installed on a selection of the bare part of tubes close to the upper and lower headers. Transient temperatures of tubes directly in line with the pipe branches on inlet headers and/or outlet headers need to be compared with adjacent tubes, and also with those furthest from an inlet and outlet branch with smaller pressure drops through the tubes. Tubes at the ends of modules may also be exposed to hotter gas leaking past upstream rows and are vulnerable to quench cooling by condensate trapped during startup.

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- The temperature of tubes in the rows downstream of attemperators should be measured to identify anomalies between tubes immediately opposite the pipe branch and the inlet header and also to assess whether there is significant variation in steam temperature between tubes in different panels caused by maldistribution of spray water.
- Evaporators can also develop significant transient temperature differences between the gas inlet row and subsequent tube rows and the downcomer. If design analysis of HP, IP and LP evaporator circuits has demonstrated that the thermal stresses developed by a temperature difference of 100°C (212°F) between the gas inlet row and downcomer ensures a sufficient cyclic life then there is no purpose in installing temporary thermocouples in the evaporator. However, if a temperature difference between front row tubes and downcomer significantly smaller than 100°C (212°F) has been used for determination of the peak thermal stresses in downcomers, pipes, tube banks and risers, then thermocouples should be installed to validate the peak transient temperature differences. Typical locations would be at the top and bottom of a few front and rear row tubes, a downcomer and pipes.

The method used for attaching thermocouples to tubes and headers must ensure that the process used to spot weld the thermocouples to tubes and headers causes no damage to the substrate material, and ensures that each thermocouple measures the metal surface temperature. To do so, thermocouples must be welded to the tube/header surface, because thermocouples clamped to the tubes generally produce inconsistent, unreliable measurements. The thermocouples must be covered with insulation to ensure that they are not influenced by convection from the hotter gas or radiation from duct liners. A procedure for spot welding thermocouples to tubes and headers that has been successfully used on several HRSGs is provided in Appendix B of Reference [10-1].

10.4 Confirming that Drain and Vent Systems Are Working as Designed

Action 10.4 *Confirm that drain and vent systems are working as designed.*

Rationale: *If condensate cannot be drained the result will be high tube-to-tube temperature differences and thermal shock at tube holes and inner surfaces of headers. Similarly, deficient venting is a source of significant thermal stress.*

Potential HRSG Damage: *Thermal fatigue, corrosion fatigue, thermal quench overload, water induction in the turbine, increased deposition and corrosion, flow-accelerated corrosion.*

A number of factors will influence the ability to drain and vent systems to properly perform their functions. For example, for removal of condensate for HP superheater and reheater tubes these include: (i) correct sizing, arrangement, routing of pipes, (ii) size of drip legs, (iii) size, location and speed of operation of isolation valves of the HP superheater and reheater drains systems, and (iv) the sizing, relative elevation and design rating of the blowdown vessel.

Thermocouples attached to the bottom and top of tubes in each section of the HP superheater and reheater downstream of drain connections, some on the tubes opposite the inlet pipe on the downstream and others on tubes more remote from the inlet branch, will confirm during the series of test startups and shutdowns discussed in Section 10.3 whether or not the HP superheater and reheater drains systems are correctly designed, installed and operated correctly.

10.5 Fine-Tuning the Distributed Control Systems (DCS)

Action 10.5 *Distributed control system (DCS) controls should be tuned to adjust the timing of sequence actions and controlled ramp rate characteristics for CT power/gas exhaust temperature and flow, HP steam pressure, etc, to be compatible with design life calculation assumptions.*

Rationale: *To minimize damage caused during various unit transients and during normal on-line operation.*

Potential HRSG Damage: *A variety of mechanisms, most notably, thermal fatigue, corrosion fatigue, and creep fatigue.*

Important actions include:

- Tests to demonstrate that the combined cycle unit can perform under the intended extent of automatic sequence and modulating controls by the DCS and/or turbine controls without operator intervention for cold starts, normal shutdowns, hot HRSG starts after an overnight offload, warm HRSG starts after 30 hours offload, cool HRSG starts after a weekend offload.
- Tests to demonstrate that the combined cycle unit will continue to operate stably under automatic controls without operator intervention, with all protection systems in service, and with all conditions remaining within the acceptable design limits during the transient following all predictable major upset events including:
 - Load rejection tests from various initial outputs.
 - Rapid load runbacks on the CT.
 - Rapid load runbacks on the ST.
 - ST trip.
 - Trip of one CT on a combined cycle block comprising two or more CT/HRSGs with a single steam turbine from various initial combined cycle loads.

10.6 Refining Cycle Chemistry and Chemistry Controls During the Commissioning Phase

Action 10.6 *Follow the six step process and associated actions detailed in the following section to evaluate unit cycle chemistry, validate decisions made during design, to fine tune operating procedures, and to judge the efficacy of control systems.*

Rationale: *To aid in the optimization of boiler water and feedwater treatments, the minimization of corrodant ingress and concentration and the reduction of corrosion product generation and transport.*

Potential HRSG damage: *All cycle chemistry induced mechanisms including deposits, underdeposit corrosion, pitting, stress corrosion cracking, and corrosion fatigue.*

10.6.1 Introduction

For reliable Heat Recovery Steam Generator (HRSG) and combined cycle plant operation, it is essential that all aspects of the cycle chemistry program be carefully evaluated as part of the unit commissioning process. Failure to do so essentially means that the unit is placed in commercial operation without optimization of the treatments applied to feedwater and boiler water. Even in those cases where the original treatment selections ultimately prove to be correct, there will be some impacts on unit availability and reliability because the treatments were not optimized as part of the commissioning procedure. In instances where the original treatment selections are inappropriate, the risks of component damage and failures, and of efficiency losses and other performance penalties are quite substantial. The costs of associated unit availability losses can greatly exceed the financial benefits, including contractual incentives, derived from rushing a new unit into commercial service without effective commissioning assessments of the chemistry [References. 10-1 and 10-2].

In order for the chemistry commissioning process to be effective, it is imperative that all of the equipment and facilities intended to establish, monitor and control the chemistry be in place and functioning as intended. Taking the actions needed to do so is a most important but occasionally disregarded aspect of the commissioning process. Many of these actions actually should be initiated prior to initial operation of the HRSG while others must be taken at this time.

10.6.2 Procedure

The cycle chemistry commissioning process consists of a number of activities. Ideally, the first steps are taken during the design and construction phases of the project. Those activities which can only be done during initial HRSG operation can, and should, be planned and scheduled well in advance, this in order to ensure that the necessary resources can be secured. This is important to consider during the procurement process since the control of and responsibility for the unit still rests with contractors at this time.

For discussion purposes, the cycle chemistry commissioning process for a new HRSG unit has been defined to consist of the following steps.

- Step 1: Pre-commissioning Activities
- Step 2: Initial Cycle Chemistry Commissioning Activities
- Step 3: Cycle Chemistry Baseline Monitoring-Feedwater
- Step 4: Cycle Chemistry Baseline Monitoring-Drum Evaporators
- Step 5: Baseline Chemistry Data Review and Assessment
- Step 6: Cycle Chemistry Optimization Activities

Organizations using these guidelines are encouraged to customize them to their own particular situation and to work with parties responsible for unit design, construction and startup to facilitate proper cycle chemistry commissioning as part of the overall process of delivering a new combined cycle unit that will meet expectations for high reliability.

Step 1: Precommissioning Activities. The key activities here are to make an objective assessment of the unit's cycle chemistry needs and to then use this information to select the feedwater and HRSG evaporator treatments to be used during the commissioning period [10-2]. Chapter 5 of this report provides details as to how to proceed with determining the design of the cycle chemistry system while Chapter 8 outlines the instrumentation requirements needed to support the various treatment approaches. Other aspects of the cycle design, for example, layup requirements, chemical feed systems and laboratory testing capabilities, should consider the results of these activities. If this process is followed properly, the prospects are generally good that the commissioning work will verify that the selected treatments are in fact suitable for use during initial commercial service operation.

Prior to unit and cycle chemistry commissioning, it is necessary that hydrostatic testing of the unit, as well as preoperational cleaning activities be completed. Ideally, water produced with the permanent makeup water treatment system will be used for these activities. The ability of this system to provide water at the rate, capacity and purity levels intended should of course be verified as part of the unit commissioning activities. During hydrostatic testing, provision should be made to verify flow through sample lines and chemical feed lines. Operability of the blowdown system of individual drum evaporator circuits should also be verified at this time. This approach helps to ensure that the cycle can be effectively monitored and controlled during the commissioning period.

Step 2: Initial Cycle Chemistry Commissioning Activities. It is assumed that the system has been filled with high purity water, preferably deoxygenated, as would be done for any unit startup. Initial actions involve establishing sample flows to on-line analyzers and grab sample collection points, and verifying the operability of chemical feed systems. In units with condensate polishers, the functionality of this system should be demonstrated during cleanup of the feedwater system prior to and/or initial operation of the combustion turbine. Performance of the deaerating heater in units, which include them, should be monitored after a steam flow to the unit has been established.

As heat is introduced to the HRSG, the blowdown system capability in drum evaporator circuits will be much more rigorously tested (by control of level as the water swells) than was possible during hydrostatic testing. The ability to use blowdown as a means of controlling evaporator chemistry should be evaluated during the commissioning period. The purity of steam generated in each HRSG circuit should be monitored carefully during the commissioning period as the steam turbine is the most vulnerable component in the cycle with respect to tolerance of deviations from normal chemistry [10-2]. Carryover tests should be conducted to evaluate the performance of the steam separators in drum evaporator circuits.

During initial commissioning operations, the intent should be to establish selected chemistry conditions in the condensate, feedwater, evaporator water and steam of the HRSG cycle. This should, and generally does, encompass a variety of operating loads and pressures as may be necessitated during the commissioning process. It is of course essential to verify that cycle contamination is not present or exists only at levels, which can be controlled by operating personnel so as not to compromise the integrity of the unit. Primary emphasis should be placed on measurement of the core parameters (see Section 8), with additional testing performed as needed to verify the instrument data, investigate any unusual readings and/or provide any supplemental chemistry data that may be needed.

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Step 3: Cycle Chemistry Baseline Monitoring-Feedwater. First, it is necessary to establish that the cycle is not subject to detrimental levels of contamination, that steam purity is acceptable and that the feedwater chemistry selected for commissioning has been properly applied. Then, a more extensive monitoring should be performed to ensure that the chemistry is suitable and to determine if additional adjustments to optimize it are required. This step is necessary to avoid or minimize the risk of subsequent problems. These include generation, transport and deposition of corrosion products. It also consists of ensuring that problems such as flow-accelerated corrosion (FAC), HRSG tube failures involving underdeposit corrosion, HRSG tube failures involving overheating, steam turbine capacity and efficiency losses, etc., are not occurring and are not likely to occur after the unit enters commercial service operation.

Operating personnel should continue to watch for cycle contamination and maintain feedwater chemistry in the selected target ranges throughout the baseline monitoring campaign. As with the initial efforts of Step 2, it is best if the baseline monitoring period includes a range of operating conditions, preferably including one or more startup and shutdown cycles. Since any once-through evaporator circuits will be on the same treatment as the feedwater system, the baseline monitoring of the evaporator water treatment may be performed in parallel with the feedwater baseline monitoring. Additional considerations for drum evaporator circuits, particularly those applying solids-based treatments, are presented in Step 4.

Key objectives of baseline monitoring of the selected feedwater treatment are to:

- Further quantify selected chemistry parameters and demonstrate their effective control.
- Determine the need for a reducing agent as part of the feedwater treatment. (Generally, this will be known in advance if the initial treatment selection was made properly, especially for all-ferrous feedwater systems.)
- Quantify and assess corrosion product transport, with emphasis on iron and (if included in the feedwater system design) copper.
- Confirm acceptable performance of the makeup water treatment system, chemical feed systems, condensate polisher (if present) and deaerator (if present).
- Confirm condenser integrity (with respect to dissolved solids ingress) and performance (with respect to air ingress).

Continued surveillance of steam purity is also needed at this time. Performance of acceptance testing of mechanical carryover in drum evaporator circuits may be possible at this time if the treatment is volatile.

Metals transport characteristics during the baseline monitoring period are the prime indicator of the suitability of the selected treatment and also assess the potential for two-phase FAC. Any of the feedwater treatment choices outlined in Chapter 5 should easily be able to ensure iron level of <5 ppb; with additional optimization, this should be further reduced to <2 ppb. In cycles, which include copper in the feedwater system (and treatment with a reducing agents), both iron and copper levels should each be <2 ppb.

Step 4: Cycle Chemistry Baseline Monitoring-Evaporator Water (Drum Circuits).

Monitoring of the evaporator water in the individual drum circuits is relatively straightforward,

especially in cases where there is no treatment other than that applied to the feedwater. As for the feedwater, the baseline monitoring campaign for evaporator water should include one or more shutdown/startup cycles and operation at varying loads and pressures. Parameters, which should be assessed, include sodium (free hydroxide), cation conductivity, silica, pH, iron, and copper (if present in the feedwater system). Supplemental testing for chloride, sulfate and other anions is desirable and strongly suggested if cation conductivity readings cannot be controlled without use of constant blowdown.

In evaporator circuits treated with trisodium phosphate, additional monitoring of sodium, phosphate, pH, etc. is required. Operation at various loads with the blowdown closed is required to determine the maximum phosphate solubility, particularly if equilibrium phosphate treatment is to be used. With caustic treatment, the permissible levels of free sodium hydroxide are very low (<2 ppm). During the commissioning period, care must be taken to avoid overfeed of treatment. Also, the feedwater must be checked to ensure no contributions of caustic from makeup treatment equipment or condensate polishers.

Analysis for organics is also helpful, particularly if the makeup water supply is high in TOC (>100 ppb) or the treatments in use include any organic-based treatments. Concentration of organics in LP evaporators is of special concern since the operating environment does not ensure thermal degradation of all species; concentration of reducing agents has been observed, which increases the potential for FAC. Concentrated levels of organics have also been observed in the evaporator circuits. The level of reducing agent present in the LP evaporator water should be monitored and controlled to avoid an environment conducive to FAC. The circulation ratio and carryover rate should be checked as part of the cycle chemistry commissioning process. Gas temperature profiles should also be developed as part of chemistry commissioning, this to identify any deficiencies which could facilitate activation of FAC, deposition problems, and solids dryout. These data become important in establishing a chemistry profile of the unit; such information is of great benefit in short-term and future assessments of chemical treatment suitability.

Step 5: Baseline Chemistry Data Review and Assessment. Upon completion of baseline monitoring, personnel responsible for cycle chemistry must make an objective review of the results to determine if the selected treatments are suitable for use in commercial operation and if additional optimization and customization is needed. Also, any problems with equipment that may have contributed to chemistry control problems must be accounted for during the review and assessment activities. The inability to consistently attain any of the chemistry guideline values associated with the selected treatments must be considered during the baseline data assessment process. However, the following observations are clear indicators that a problem exists or that the selected treatment is either not suitable or requires further optimization [10-2].

- Condenser air-inleakage and/or cooling water ingress are excessive.
- Effluent purity from makeup treatment system or condensate polisher is insufficient.
- Performance of deaerator heater is unsatisfactory.
- Feedwater cation conductivity subject to increases to $> 0.2 \mu\text{S}/\text{cm}$.
- Increased iron and/or copper levels in feedwater.
- Feedwater ORP oxidizing (cycles with copper in feedwater system only).

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- Unable to maintain evaporator chemistry with blowdown closed.
- Evaporator water subject to pH depression either in normal operation or during shutdown/startup cycles.
- Extended unit startups due to chemical holds.
- Evaporator iron concentrations >>100ppb.
- Evaporator cation conductivity > 2 $\mu\text{S}/\text{cm}$ (HP/IP), > 3 $\mu\text{S}/\text{cm}$ (LP); values adjusted for phosphate treatment where used.
- Evaporator water TOC > 200 ppb
- Drum carryover rate in excess of design criteria, sodium in steam > 3ppb, silica in steam >10 ppb, cation conductivity > 2 $\mu\text{S}/\text{cm}$.
- Low circulation ratio and/or excessive (variations of > 100°C/180°F) gas temperatures in evaporator circuits.

If any of these problems are encountered, further appraisal of cycle chemistry is needed.

Step 6: Cycle Chemistry Optimization Activities. The initial step is to identify and correct any problems not directly attributable to the cycle chemistry selections. Inadequately performing equipment such as the makeup system, condensate polisher system, the condenser, or the deaerating heater are clear examples of problems of this type. Any such deficiencies should be addressed prior to acceptance of the unit.

Once this is done attention should be directed to the cycle chemistry treatments selected for the feedwater and evaporator water. If many of the indicators listed in Step 5 are of concern, it is generally advisable to repeat the treatment selection process (See Step 1 plus Chapters 5 and 8 of this report). If this process indicates that other treatments than the ones used during commissioning need to be considered, an assessment of actions needed to accomplish this must be made. Also, a repeat of the baseline monitoring programs for feedwater and evaporator water (Steps 3 and 4) is needed.

In the event it is determined that relatively few and minor problems exist, an effort to optimize the selected treatments may be the proper course of action. Typically, optimization is needed to obtain the lowest possible levels of iron and copper in the final feedwater. This generally involves the following actions [10-2]:

- Optimization of feedwater reducing agent treatment level (where needed) and ORP (cycles with copper in feedwater system only) to avoid FAC and minimize copper transport, respectively.
- Optimization of feedwater pH to minimize metals transport.
- Optimization of evaporator treatment to avoid or minimize chemical hideout and return, consistent with needs to protect HRSG from contaminant ingress and protect turbine from exposure to contaminated steam.

Upon determination of the necessary modifications to the chemistry, confirmatory monitoring should be conducted to evaluate the impacts of any changes made and to determine if additional

selection and optimization of the chemistry appears warranted. Even in units where the chemistry appears to be fully optimized, it is considered good practice to periodically repeat this process as unit characteristics and needs are subject to change over time.

10.7 Monitoring Flue Gas Conditions

Action 10.7 Measure flue gas conditions to confirm (i) exhaust gas temperatures, (ii) rate of temperature changes with various transient operating conditions, (iii) distribution of flue gas flows, particularly, the location and magnitude of flue gas laning caused by distorted or missing baffles, deflected or bowed tubes, (iv) that there are no local “hot” spots nearby to duct burners, (v) that there is no excessive condensation on cold end components

Rationale: To avoid various gas side damage mechanisms caused by excessive temperatures, temperature changes, or, in the case of the cold end, condensation.

Potential HRSG damage: Excessive temperatures can lead to short term and longterm overheating thermal fatigue, excessive deposition, underdeposit corrosion mechanisms, and flow-accelerated corrosion. Temperatures too low in the cold end can lead to gas side pitting and corrosion, acid dewpoint corrosion and stress corrosion cracking

There is an important need to monitor flue gas conditions during the commissioning phase. Section 10.3 provides recommendations for measuring tube metal temperatures during transients which will provide an indirect measurement of gas velocity or temperature maldistributions. This section provides additional recommendations for direct measurements of gas temperatures, primarily during steady state periods of operation. Two of the major objectives for knowing the specific details of what is occurring on the HRSG gas side are to:

- Establish and document the actual unit performance to illustrate that the equipment thermal performance guarantees are met, such as by ASME PTC 4.4.
- Identify any location where a significant deviation in predicted temperatures exists, which could potentially lead to premature pressure part deterioration.

10.7.1 Instrument and Miscellaneous Connections

The following examples indicate sample minimum requirements for temporary and permanent instrumentation to monitor gas side operating conditions during commissioning:

Temporary Instrumentation

- Use three 38 mm (1 ½ inch) pipe size couplings for shielded high velocity temperature probes on the gas side at the entrance of the HRSG, between each section of the HRSG, and at the exit of the unit (exhaust duct). Connections should be provided just downstream of the CT interface near the permanent inlet duct thermocouples. The connections shall be for insertion of, and support of, a temporary thermocouple grid to be used during HRSG performance testing. Temporary thermocouple grid elements should also be provided upon request. The grid should consist of stainless steel pipes arranged to establish a grid of 24

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measurement points. The thermocouple leads should extend to a temporary data logger to be provided by the supplier.

- Use one 38 mm (1 ½ inch) pipe size coupling for exhaust gas pressure gauge downstream of the combustion turbine exhaust, at the inlet to the HP superheat section, across future SCR, and between each section of the HRSG.
- Install temporary thermocouples on at least 20 percent of the tubes entering the outlet header of each economizer, superheater and reheater section. Of these, use two (2) shielded (permanent) tube skin thermocouples that are installed on the outlet tubes entering the outlet headers of all HRSG sections, located on each side, directly adjacent to location where baffles exist, such as between modules and along each side of the HRSG enclosure wall.

Permanent Instrumentation

- Use exhaust test ports at six locations in the HRSG inlet duct, at two locations between each superheater, reheater, evaporator, economizer and feedwater preheater sections and at six locations in the stack transition for Turbine Exhaust Gas (TEG) temperature measurement.
- Use TEG test ports provided upstream and downstream of the SCR and CO catalyst beds as required to verify SCR and CO performance, including local flow distribution, pressures and temperatures consistent with the catalyst manufacturer's recommendations, but not less than six (three each side) at each location.
- The TEG thermowells provided should extend into the innermost two-thirds of the exhaust gas path cross sectional area. The internal thermowell length should be 1 m (3 feet) for HRSG internal widths exceeding 5.5 m (18 feet).

10.7.2 Testing Protocol For HRSG Characterization

To evaluate current HRSG operation and to provide data for diagnosing the potential for TEG temperature and flow maldistribution, which would likely contribute to tube failures, it is necessary to conduct a series of tests to establish baseline performance. These tests will provide boiler data regarding current operation, TEG flows, pressures and temperatures, along with economizer, superheater and reheater metal temperatures.

These tests will characterize and document operation for the following operational regimes:

- Baseline conditions, unfired conditions
- Maximum load attainable, fired with duct burners (if applicable)
- Minimum load attainable

These tests are intended to establish baseline unit performance and to form the basis for diagnosing potential problems associated with pressure part reliability of the overall system. In order to satisfy the requirements necessary to achieve this objective, a matrix consisting of three steady state tests and one transient operation test (in addition to the transient tests discussed in Section 10.3) should be developed.

An example test matrix that will accomplish the goals of this test program is provided in Table 10-1. The matrix represents a general approach to the program and not necessarily a rigid step-by-step procedure. Changes to this matrix can occur as the testing progresses.

Testing should commence within thirty days of the unit being “Substantially Complete” and after the unit has stabilized from an operational change. The stabilization period is typically 30 to 45 minutes. The amount of time to conduct a particular test will generally be controlled by the level of data required.

Table 10-1
Example HRSG Pressure Part Reliability Test Matrix

Test	Load (MW)	Description	CT Conditions	Data Requirements				Comments	Hours
				HRSG Gen'l Perf.	TEG Temp. Profiles	Tube TCs	CT Outlet Conditions (Flow, Analysis)		
1	MCR	Baseline	As Found	X	X	X	X		4
2	MCR	Maximum Load attainable, fired with duct burners(if applicable)	As Found	X	X	X	X		4
3	MCR	Minimum Load attainable (Reduced Pressure, if applicable)	As Found	X	X	X	X		4
4	--	Ramp test – Load raising	Normal, within HRSG OEM guidelines	X	X	X	X	See Section 10.3 for other operational transients measurements	2

Notes: Additional detailed tests may be added to a particular test series as required to demonstrate severity or root cause.

MCR = maximum continuous rating

This test matrix should be designed to evaluate temperature variations within specific pressure part sections that could contribute to premature tube failures identified in EPRI's HRSG Tube Failure Manual [10-1] and assist in identifying the potential root cause(s).

10.7.3 Test Data Required – Gas and Tube Metal Temperatures, Pressures, Fuel

Flue gas temperatures are required. These temperatures typically require grids for accurate measurements. Grids are necessary due to the fact that the temperature is typically not uniform across a duct and multiple measurements are required to obtain an accurate value. Flue gas temperature measurements should be performed at the same locations as the gas analysis sampling discussed above for the HRSG inlet section.

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HRSG instrumentation will also be monitored during the tests, including the following:

- Gas temperatures obtained at the outlet for estimating maldistribution. For assessing impact, a peak-to-peak temperature differential of 28°C (50°F) is considered normal and acceptable.
- Metal temperatures should be obtained from the permanent and temporary surface type thermocouples installed on at least 20% of tubes, as described above.

System Pressures

In addition to the data available from exiting HRSG sensors, draft system information should also be recorded. Static pressure data are required for the each boiler section. These data may be obtained by installing a pressure tap in an existing port connection at each of the access areas located between respective HRSG sections. The ports used should be located at approximately the same elevation.

Flue Gas Sample Analysis

If cold end fuel ash deposition or tube metal temperatures lower than the flue gas dew point are anticipated to be potential concerns then deposition probes, flue gas sampling and analysis and dew point measurements in the cold end regions of concern should be made during each of the four tests listed in Table 10-1.

10.8 Unit Data Required

Action 10.8a During commissioning testing collect, archive and review the temperatures, pressures, and flow rates to verify the design margins that are key to the prevention of pressure part failures or in-service degradation.

Action 10.8b If unanticipated or undesirable pressures, temperatures, or flow rates are measured during steady state or transient operational tests then perform more detailed assessments and/or measurements to determine their root cause.

Rationale: To confirm that the key damage influence factors such as temperature, pressure, and fluid flows are within acceptable limits and will not provoke pressure part failures or accelerated in-service degradation.

Potential HRSG damage: All damage mechanisms.

There are three major areas of data to be collected from the HRSG and the control room instrumentation: temperature, pressure and flow. A general discussion of these three areas and other test support data follows.

The unit operating data identified in the preceding sections should be obtained as available for each test. During short duration tests (approximately 1 to 2 hours), data should be obtained as frequently as possible but no less than at the beginning and end of the test. Data should be obtained approximately every hour during longer tests.

The intent of this required collection of operating data is to develop sufficient information to evaluate current individual section performance as well as to permit assessment of the flue gas temperature and tube temperatures. From this database, the impact of a lateral and vertical TEG distribution on tube temperatures can be assessed. If the required instrumentation is not available at each location, uncertainties regarding metal temperature distribution performance will occur.

10.8.1 Temperature Measurements

The following is a list of temperatures that should be collected from the control room instrumentation or plant historian for each of the tests listed in Table 10-1:

Water/Steam Temperature

- Boiler Feedwater
- Economizer Inlet
- Economizer Outlet each side
- Main Steam
 - Primary SH each side
 - Primary SH individual outlet tubes
 - Secondary SH
 - Secondary SH individual outlet tubes
- Reheat Steam
 - Inlet header each side
 - Reheat outlet
 - Reheat outlet individual outlet tubes

Gas Temperature

- CT Exhaust
- Duct Burner/HRSG Inlet
- FSH and RH Outlet
- HP Evaporator Outlet
- SCR/CO Catalyst outlet
- HP Econ Outlet
- IPSH Outlet
- IP Evaporator Outlet
- IP Economizer Outlet
- LP Evaporator Outlet
- FW Heater Outlet

10.8.2 Pressure Measurements

Most of the pressure measurements required for the tests can be obtained using existing plant transmitters. Pressure data should be collected both during the steady state testing discussed in Section 10.7 and the transient testing discussed in Section 10.3. The measured pressures should be compared with the anticipated design values. The fluid pressure and temperature combinations should also be reviewed to assure that their combination does not exceed the design limit especially during transients or low load or duct burner operation. This data may also

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be useful to assess other design margins such as the potential for localized steam film formation. The following is a list of pressure measurements required during testing.

Water/Steam/Fuel Pressure

- All Steam Pressure
- Feedwater
- All Economizer Inlet
- All Economizer Outlet
- All Evaporator Outlet
- Reheat Outlet
- Reheat Spray
- Superheat Spray
- Burner Gas Pressure

Gas Pressure

- CT Exhaust
- Duct Burner/HRSG Inlet
- FSH and RH Outlet
- HP Evaporator Outlet
- SCR/CO Catalyst outlet
- HP Econ Outlet
- IPSH Outlet
- IP Evaporator Outlet
- IP Economizer Outlet
- LP Evaporator Outlet
- FW Heater Outlet

The pneumatic signal lines to air/gas pressure transmitters should be blown out to ensure clean lines prior to testing.

10.8.3 Flow Measurements

The primary flow measurements required during testing are feedwater, steam, air, flue gas, and fuel flow. These flows are to be used for the purpose of determining the load at which the HRSG is operating and to enable assessment of operating conditions which may lead to increased risk of pressure part damage such as flow accelerated corrosion, thermal quenching induced fracture, flow induced vibration fatigue, etc. The following lists some of the flow rate measurements that should be collected and reviewed during steady state and transient commissioning operational tests:

Water/SteamFlow Rate

- Feedwater (LP, IP, HP)
- Main Steam
- Hot Reheat Steam
- Superheat and Reheat Sprays
- Auxiliary Steam

Air/Gas/Fue Flow Rate

- TEG Flow
- Fuel Flow to CT
- Fuel flow to Duct Burner (if applicable)

Position Settings

FD Fan Dampers (if applicable)

Superheat Spray

Reheat Spray

Air Registers

These conventional bulk flow rate measurements may not be sufficient to identify potential problems associated with flow rate maldistributions caused by gas velocity or temperature maldistributions or poor distribution of attemperator spray fluid. The primary indicator of these types of problems during the commissioning testing will be obtained from the thermocouple measurements discussed in sections 10.3 and 10.7. If undesirable temperature maldistributions are measured then more comprehensive gas or fluid flow rate measurements may be needed to determine their root cause.

10.8.4 Test Support Data

In addition to the temperature, pressure, and flow rate test data it is recommended that the following control room test data is collected and archived during each of the steady state and transient operational tests:

Load: Gross, Auxiliary and Net

Calculated Plant Heat Rate: Gross and Net

Atmospheric Pressure

Control Room O₂, CO and NO_x and CEMS data

Date and time

10.9 References

[10-1]. Dooley, R.B., K.J. Shields, S.R. Paterson, T.A. Kuntz, W.P. McNaughton, and M. Pearson, *Heat Recovery Steam Generator Tube Failure Manual*, 1004503, EPRI, Palo Alto, CA., 2002.

[10-2]. Dooley, R.B., A. Aschoff, M. Ball, A. Bursik, F. Pocock, and K.J. Shields, *Interim Cycle Chemistry Guidelines for Combined Cycle HRSGs*, TR-110051, EPRI, Palo Alto, CA., November 1998.

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EXAMPLE SHUTDOWN AND STARTUP PROCEDURES

Section 4-3 and Subsections 4.3.2 to 4.3.7 describe the key objectives and principal actions for combined cycle shutdowns and startups from different initial conditions in the HP section of the HRSG to minimize thermal fatigue damage in the critical parts of HP superheater, reheater and HP drum.

The detailed example shutdown and startup procedures presented in this section are particularly addressed to combined cycle plants employing larger capacity combustion turbines, such as those of F- and G-class, or equivalent.

These examples are not intended to be comprehensive protocols but address those aspects of integrated combined cycle shutdown and startup procedures that strongly influence the rate of fatigue and creep fatigue life expenditure in the critical components of the HRSG.

A.1 Normal Shutdown

- Before commencing normal shutdown, switch the HP steam turbine control into constant inlet pressure control mode with an inlet pressure setpoint a few psi or kPa above the prevailing HP pressure. Also, set the HP and HRH bypass valve inlet pressure control set points to shadow a few psi above the prevailing HP and HRH steam pressures. This is done so that when steam is diverted from the steam turbine to the HP bypass and HRH steam dump by controlled closure of the steam turbine inlet control valves to the shut position (and at a rate that ensures no pressure fluctuations in the HP drum), the HP and HRH bypass valve will open progressively and control the HP and HRH pressures at similar values.
- When the HP and HRH steam temperatures begin to reduce significantly below their normal maximum, transfer steam flow from HP and IP steam turbines to the HP bypass and reheat steam dump. Prior to shutdown, the HRH steam dump valve should be enabled to open if the HRH pressure rises slightly above the immediately prevailing HRH pressure. For the different types of the largest CTs, the HP steam temperature starts to fall between 35 & 50% of CT load.
- When the HP and HRH outlet temperatures begin to reduce below their design maximum, control the rate of CT deloading to maintain a pre-determined rate of reduction in CT exhaust temperature down to full-speed no load (FSNL). This will lower the superheater and reheater steam and metal temperatures at a somewhat slower rate. During this period of controlled deloading of the CT, slowly ramp up the HP and HRH bypass inlet pressure control setpoints to raise the HP and HRH pressures close to their normal design maximum.
- Hold the CT at minimum load, with minimum CT exhaust gas temperature, for long enough to allow the bulk of the superheater outlet header to cool to close to the gas temperature.

Example Shutdown and Startup Procedures

- Minimize/avoid CT post-shutdown cool down cranking.
- Bottle up the HRSG immediately upon CT shutdown for minimum drum pressure decay. All feedwater, spraywater, HP steam, blowdown, drains, and vents on the HRSG should be shut and double isolated in order to minimize the rate of HP drum pressure decay and thereby maximize the HP saturation temperature to which much of the HRSG cools after shutdown.

A.2 Shutdown Sequence for Maintenance Access

- Prior to commencing the shutdown, put the steam turbine in inlet pressure control with the HP setpoint at the minimum allowable by the HRSG for the prevailing steam flow rate.
- Ramp down the CT(s) load (together) and reduce the HP bypass setpoint as steam flow reduces at the maximum rate allowed for the HP drum saturation temperature until CT exhaust temperature falls below 565°C (1050°F).
- Set the HP and HRH bypass valve inlet pressure control setpoints at the prevailing HP and HRH steam pressures.
- Transfer the steam from the HRSG to be shutdown into its HP and HRH bypasses and then continue to deload the CT to reduce the exhaust gas temperature at a constant rate appropriate for the thickness of the HP superheater outlet header. Simultaneously, lower the HP bypass setpoint progressively to about 5.2 MPa (750 psia) in accordance with the recommended rate of saturation temperature reduction.
- When the CT is at minimum load, shut down the CT.
- After the CT flames out, lower the HP bypass setpoint to maintain the HP saturation temperature not more than 90°C (162°F) below the measured HP superheater header midwall temperature, or lower the HP drum saturation temperature at the maximum rate permitted for pressure-lowering, whichever is the slower. If the HRSG has no measurement of the HP superheater outlet header temperature, some other criteria must be established to ensure that the HP superheater is not cooled too fast.
- After the CT is on turning gear, the CT can be run intermittently at purge speed while continuing to control the rate of fall in the HP saturation temperature within the above two limiting criteria.
- When the HP pressure is less than 0.69 MPa (100 psia), open the vents, close the bypass valves and drain the HRSG.

A.3 Cold Startup

- Well before commencing CT startup, put the HP superheater and reheater drains in auto, or if not automated, open all HP superheater and reheater drains to remove condensate prior to startup. Drain flow rates are low when there is no pressure to assist removal.
- After CT startup, where the HP superheater and reheater drains are not automatically controlled by condensate pots with level switches, leave the drains open until the CT exhaust temperature exceeds about 370°C (700°F).

- Give the HP bypass a low target setpoint, around 0.41 MPa (60 psia), to perform initial heating of the HP drum at as low a saturation temperature as possible. In practice, the HP bypass volumetric capacity may cause the HP pressure to exceed the initial target set point before the HP bypass valve begins to control the inlet pressure. The HRH bypass setpoint will be based on the HP pressure. Open HP vents.
- Start the CT and add minimum load after synchronizing for the initial heat soaking of the HRSG. Close the HP vents at 0.31 MPa (45 psia). When the HP bypass valve begins to control the HP pressure, adjust the target setpoint to match the HP pressure. The HRSG OEM provides recommended ramp rates for HP saturation temperature. Hold the HP pressure initially for the period to bring the saturation temperature increase into line with the recommended HP saturation ramp rate. Then increase the HP bypass setpoint to raise the HP saturation temperature, at the rate recommended by the HRSG OEM, until the HP pressure reaches a hold pressure to complete heat soaking of the HP drum and superheater, usually between 2.76 to 4.14 MPa (400 and 600 psia). This hold pressure is influenced by the minimum steam flow required to be available by the steam turbine before rolling. Throughout this period, the CT has remained at minimum load.
- When the HP superheater midwall temperature is less than 90°C (162°F) below the HP steam temperature, start to ramp up the CT exhaust gas temperature to raise the HP steam temperature, at a rate to be determined, until the steam temperature matches the steam turbine requirement for roll-off. The time required to heat the superheater header to within 90°C (160°F) of the steam temperature and the ramp rate in the HP steam temperature acceptable to the HRSG are strongly influenced by the thickness of the HP superheater and reheater headers. After rolling the steam turbine, maintain steam temperature to match steam turbine and HP superheater header requirements. The ramp rate selected for the HP steam temperature is dictated either by the steam turbine or by the HRSG HP superheater, whichever is the lower rate of increase.
- During cold starts, for the duration of the period required to raise HP steam temperature to the full steam temperature at the maximum rate acceptable to the steam turbine and/or HP superheater header, the CT load is held below 30 to 40% in order to match the exhaust gas temperature characteristic to the steam turbine and/or HP superheater steam temperature requirements.
- The practice sometimes used to rapidly ramp CT load to 60 to 70% to get emissions into compliance, and then lowering the HP superheater and reheater attemperators setpoints to produce low temperature steam to match the steam turbine requirements, is not recommended. This is because it leads to overspraying down to the saturation temperature at the attemperator outlet, because steam flow rates are low and unpredictable during pressure raising and may transiently cease leading to overheating of tubes. Steam temperature cannot be controlled when overspraying and the excess water can cause early tube failures. Startup attemperators, installed at HP superheater outlet, are also not recommended for HRSGs intended to be cycled because they do not protect the HP superheater headers from high steam temperature ramp rates when the CT is loaded rapidly.
- After the HP steam temperature has reached its normal control temperature between 35% and 50% CT load, the unit can be loaded up to baseload without any restrictions from the HRSG. However HP pressure must still be controlled to the limit ramp rate for saturation temperature by the HP bypass valve. The optimum control characteristic for HP pressure

Example Shutdown and Startup Procedures

versus time following the opening of the HP bypass at a predetermined pressure between, for example, 2.1 and 2.8 MPa (300 and 400 psig) needs to address the following issues: 1) The rate of rise in drum saturation temperature must be acceptable to the HP steam drum for the specified design lifetime cycles, 2) the preferred time after ignition when the SCR should be put in service, which requires an HP pressure of between 6.2 and 6.9 MPa (900 and 1000 psig), and 3) minimizing heat dumped to the condenser during bypass operation.

- During the period when the CT exhaust gas temperature is being raised to bring the HP steam temperature at a controlled rate to its maximum, the HP drum pressure can be raised so that it is at or above 6.9 MPa (1000 psia) when steam temperatures are close to 565°C (1050°F) and exhaust temperature matching is concluded. The CT can then be rapidly loaded without restrictions from the HRSG or steam turbine, to any load, and the SCR can be established in operation.

A.4 Hot/Warm Startup After an Overnight Offload

Note that as the initial HP pressure becomes lower than about 3.45 MPa (500 psia), the heating of the HP drum at its allowable rate may become a critical time path factor in the startup duration. This leads some to delineate between hot and warm starts between about 3.1 MPa and 3.45 MPa (450 to 500 psia). Starts from an initial HP pressure between about 0.34 MPa (50 psia) ($T_{\text{sat}} = 138^{\circ}\text{C}$ (281°F)) to about 3.45 MPa (450 psia), ($T_{\text{sat}} = 236^{\circ}\text{C}$ (456°F)) are loosely categorized as “warm” HRSG starts.

For example, a startup from 6.9 MPa (1000 psia), ($T_{\text{sat}} = 285^{\circ}\text{C}$ (545°F)), for an arbitrarily assumed acceptable steam temperature ramp rate of 27.8°C (50°F)/min, requires about 10 minutes for the temperature ramping part of the start to raise the HP steam temperature from the initial saturation temperature of 285°C (545°F) to 565°C (1050°F). If the startup was from 2.76 MPa (400 psia) ($T_{\text{sat}} = 229^{\circ}\text{C}$ (445°F)), the comparable acceptable ramp would reduce to about 22°C (40°F)/min and in this case about 15 minutes would be required for the steam temperature ramping part of the startup. A startup from 2.07 MPa (300 psia) ($T_{\text{sat}} = 214^{\circ}\text{C}$ (417°F)) would require about 17 minutes, or from 1.38 MPa (200 psia) about 19 minutes to raise steam temperature to 565°C (1050°F).

The other component to consider is the HP drum. As with the HP superheater header, the smaller the total change in saturation temperature, the faster the allowable ramp rate. Saturation temperature in the HP drum at baseload is about 332°C (630°F). Thus a start from 6.9 MPa (1000 psia) might require 11 minutes to raise saturation temperature by 47°C (85°F), whereas for start from 2.76 MPa (400 psia), the time for comparable life expenditure to raise T_{sat} by 102°C (185°F) would be about 23 minutes, and from 2.07 MPa (300 psi) about 30 minutes.

Key events for “hot” starts after overnight shutdowns include the following:

- Seal the steam turbine glands and raise condenser vacuum.
- Put the HP and HRH bypasses in auto with the target setpoint for HP bypass set 0.2 MPa (30 psi) higher than HP pressure

- Put HP superheater and reheater drains in auto, or if not automated, open all HP superheater and reheater drains when the CT purge is initiated to remove condensate as it collects to prevent pooling or flooding in lower headers and manifolds.
- Start CT purge, runup, synchronize and apply minimum load.
- After CT startup, where the HP superheater and reheater drains are not automatically controlled by condensate pots with level switches, leave the drains open until the CT exhaust temperature exceeds about 370°C (700°F).
- Hold the CT at minimum load until the HP and HRH bypasses have opened, which should occur immediately after the CT is established on minimum load and the CT exhaust gas temperature is reduced to its minimum possible. Continue to hold at minimum load for a few minutes, until after the bypasses are opened to begin the heat soak of the HP superheater and reheater headers with steam at minimum temperature.
- If starting the first CT/HRSG block: Ramp up the CT exhaust temperature to raise the HP steam temperature at the rate allowable for the HP superheater outlet header until the steam temperature matches the steam turbine requirements for rolling the steam turbine. Simultaneously ramp up the HP pressure by progressively changing the HP bypass setpoint at the allowable rate of change of saturation temperature for the HP drum. Roll the steam turbine when steam conditions are matched.

If starting the second CT/HRSG with the other CT/HRSG and steam turbine in operation: continue the steam temperature and pressure ramps until steam pressure and temperature are matched to the other HRSG and then transfer steam flow from the bypasses to the steam turbine.

Targets:

New Combustion Turbine/Combined-Cycle
Design, Repowering & Risk Mitigation

Heat Recovery Steam Generator
(HRSG) Dependability

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