Evaluating and Avoiding Heat Recovery Steam Generator Tube Damage Caused by Duct Burners

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PRODUCT DESCRIPTION

In heat recovery steam generators (HRSGs), supplemental firing in duct burners introduces the potential for serious HRSG tube failure and damage. Duct burners that are specified, designed, and operated properly can produce a number of significant benefits. This report will assist operators in accruing these benefits.

Results and Findings

This work illustrates that HRSG tube failures and damage can be avoided by properly developing a specification and design requirements for duct burners in new units. Optimum commissioning, operation, and maintenance of the duct burners are of paramount importance. Confirming that HRSG tube sections are not overheating during operation requires a thermocouple attachment to the appropriate HRSG sections. The report includes detailed sections on both design and operations and maintenance (O&M) issues.

Challenges and Objectives

Supplementary firing through duct burners can yield a number of benefits that include increased production during peaking periods; faster total plant ramp rates; and the ability to fire lower cost, lower quality fuel. On the other hand, duct burner operation decreases overall combined cycle system efficiency, can increase total plant emissions, and can result in HRSG damage and failure. The objective of this work was to assemble the life cycle requirements for optimum duct burner operation.

Applications, Value, and Use

The techniques and processes described in this report are applicable to all types of HRSGs. Adoption of this life cycle approach will put an organization on the road to world class HRSG performance.

EPRI Perspective

To address the overall issue of HRSG tube failures (HTF), EPRI has developed a series of documents:

- *Heat Recovery Steam Generator Tube Failure Manual* (EPRI Report 1004503)
- *Delivering High Reliability Heat Recovery Steam Generators* (EPRI Report 1004240)
- *Diagnostic/Troubleshooting Monitoring to Identify Damaging Cycle Chemistry or Thermal Transients in Heat Recovery Steam Generator Pressure Parts* (EPRI Report 1008088)
- *Cycle Chemistry Guidelines for Combined Cycle / Heat Recovery Steam Generators* (EPRI Report 1010438)

EPRI is developing a shutdown/startup guideline to optimize the thermal transient behavior of HRSGs. This current document is the first of four on HRSG ancillary equipment (duct burners, stack dampers, drains, and attemperators), which has a major influence on thermal transients and thus on HTF.

Approach

The EPRI team first conducted a review of worldwide experience with duct burner operation. This included a number of thermal and cycle chemistry HTF mechanisms as well as the various design standards for duct burners. The team assembled draft and final documents in parallel with the developing startup/shutdown guideline. The road maps were developed from reported best practices.

Keywords

Heat recovery steam generator (HRSG)
Combined cycle units
Tube failures
Duct burners
Thermal transients
Monitoring and diagnostics

ABSTRACT

In HRSGs, the presence of supplemental firing in the form of duct burners introduces the potential for serious HRSG tube failures and damage. These can be avoided by properly developing a specification and design requirements for new units, and subsequently conducting optimum commissioning, operations and maintenance of the duct burners. This document addresses the complete life cycle of duct burners and provides roadmaps for each of the cycle steps. Detailed sections deal with design issues (Section 3), and operations and maintenance issues (Section 4). The appendices cover the information needed to make an assessment of potential duct burner influenced damage and two case studies.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1
INTRODUCTION

Combustion turbines (CT) produce large volumes of hot exhaust gas containing sufficient oxygen to support supplemental combustion. When a gas turbine is equipped with a heat recovery steam generator (HRSG), it is not uncommon to utilize supplemental firing to increase steam generation or temperature. Equipment used to provide supplemental firing is located either in the duct between the CT exhaust diffuser and the HRSG inlet, or more often with F-class CTs in the duct between the secondary (final) HP superheater (HPSH) and reheater (RH) sections and the primary HPSH and RH sections. Hence, these supplemental firing systems are often referred to as Duct Burners (DB).

Duct burners may be configured much like a conventional register-style burner. These generally require a source of augmentation air in addition to the CT exhaust gas. However, this report deals with the type of DB system used in the large majority of HRSGs that utilize only CT exhaust gas for combustion and has no secondary source of augmentation air. This type of DB system consists of an assembly of fuel piping (runners or rails), fuel nozzles, flame holders, exhaust-gas diffusers, and a support structure arranged in a grid pattern directly in the hot gas stream inside the HRSG duct (Figures 1-1 through 1-5).

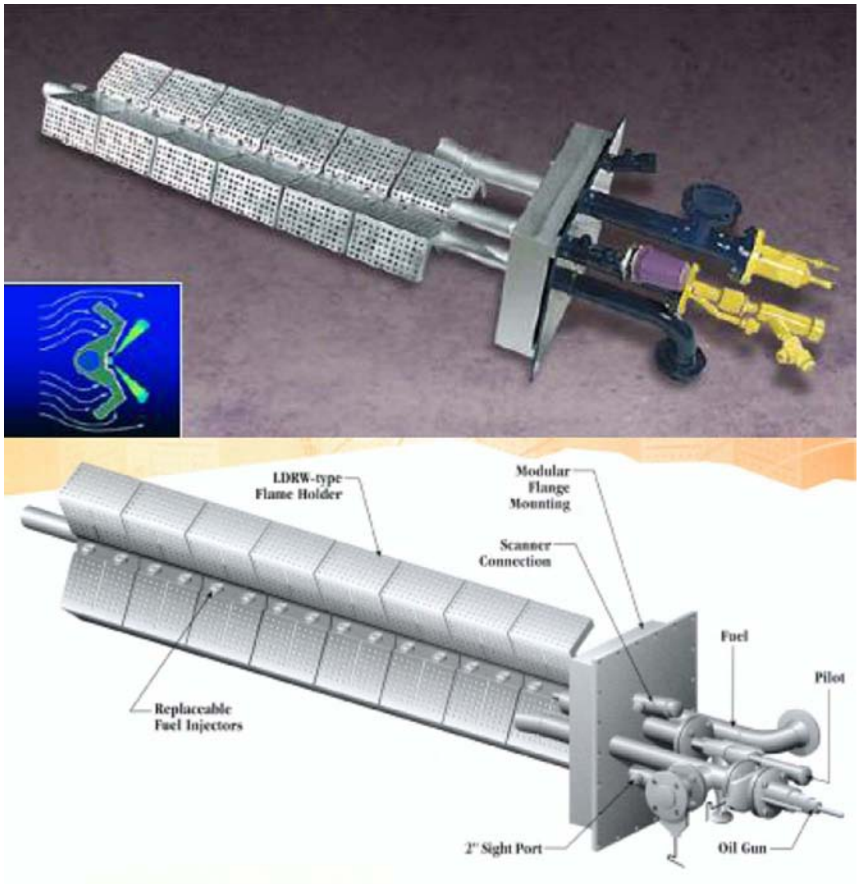

Figure 1-1
Typical Duct Burner Runner Components (Courtesy John Zink, LLC)

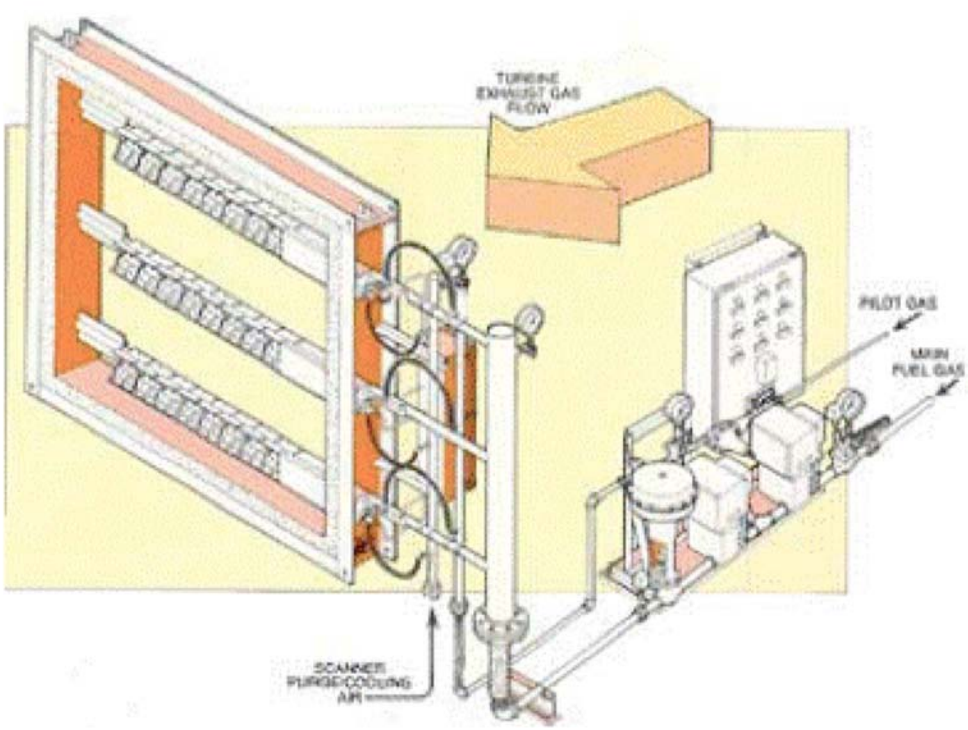

Figure 1-2
HRSG Duct Burner Array (Courtesy Coen Company, Inc.)

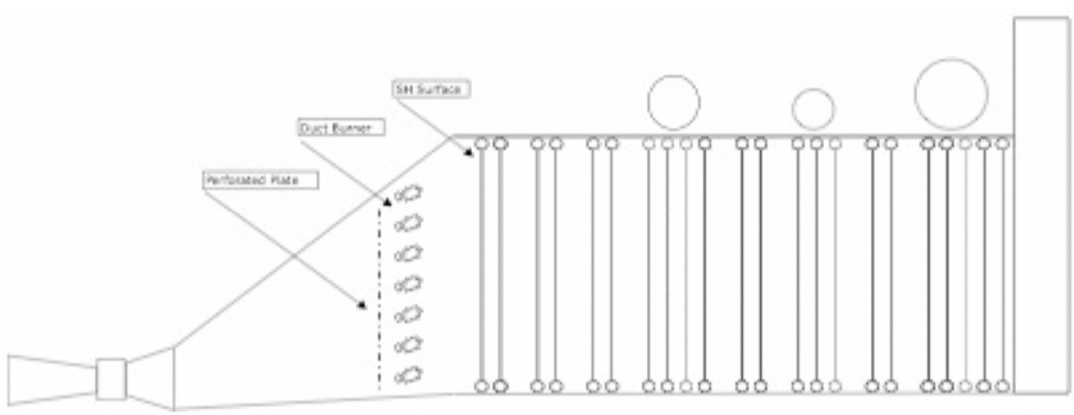

Figure 1-3
Duct Burner Installed Between a Perforated Plate Flow Diffuser and the Final Superheater/Reheater

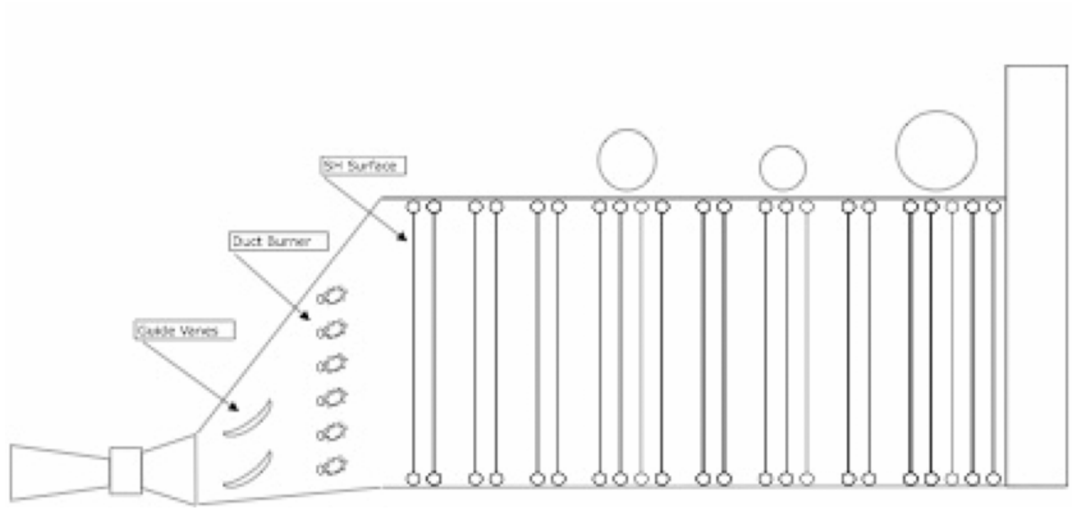

Figure 1-4
Duct Burner Installed Between Fixed Guide Vanes and the Final Superheater/Reheater

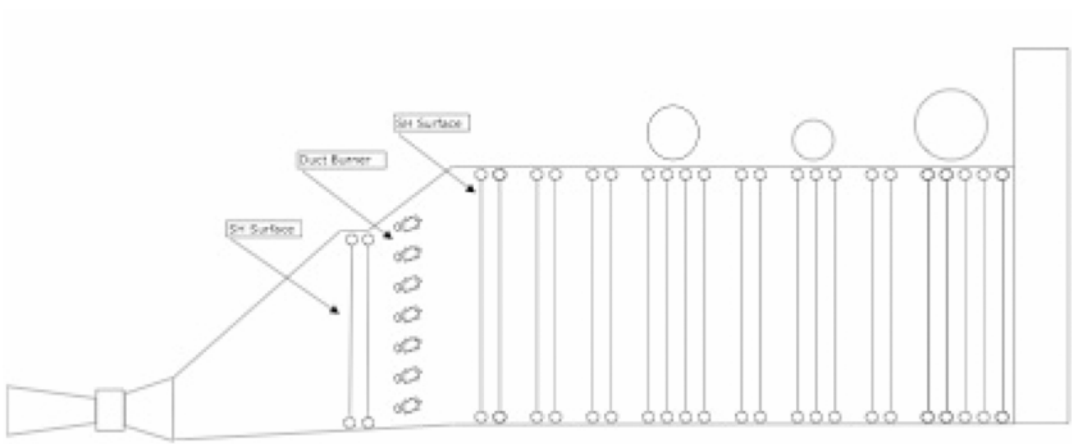

Figure 1-5
Typical F-Class Arrangement with Duct Burner between Final Superheater/Reheater and Primary Superheater/Reheater

DB systems also utilize a variety of fuel piping, valves, igniters, flame scanners, auxiliary air blowers and a burner management system all located external to the HRSG casing. The DB burner management functions generally are performed by a stand-alone system, however a few plants utilize the distributed control system (DCS) for this purpose. NFPA 85: Boiler and Combustion Systems Hazard Code, and NFPA 8506: Standard on Heat Recovery Steam Generators Systems, (which addresses the design, installation, maintenance, and operation concerns as they relate to combustion system hazards in fired and unfired HRSGs using natural gas or fuel oil), stipulates DB fuel-system configuration and burner management functions.

Supplemental firing can yield a variety of benefits, including:

- Increased combined cycle power production for periodic peaking
- Recovery of CT output lost to high temperature ambient conditions during the summer
- Faster total plant ramp rates (MW)
- Ability to fire lower cost, lower quality fuel not suitable for CT operation
- Facilitate keeping the SCR in its operating temperature range at lower CT loads*
- Ability to operate the steam cycle without the CT in service, if a fresh air firing scheme is installed
- Ability to operate in a steam load-following mode independent of CT load.* This can be advantageous in cogeneration applications

* Only in HRSGs specifically designed for DB operation at less than full CT load

Since DB operation decreases overall combined cycle system efficiency, supplemental firing is not typically used for base load operation. Another disadvantage of DB operation is that it increases total plant emissions. For this reason some plants have regulatory limitations on the total number of DB fired hours allowed annually. A typical limit is 4000 hours/year.

1.1 Purpose and Objectives

The purpose of this report is to provide designers, owners and operators of HRSGs equipped with DB information that will facilitate specifying, designing, operating, and maintaining the equipment in a manner that minimizes damage to pressure parts. Other objectives of this report are to warn operators of the significant risks of pressure part damage from retrofit of DB into an HRSG not originally designed for their use, or from operation of DB below the CT load range for which the HRSG and DB were originally designed.

1.2 Avoidance of Off-Design Operation

Even small deviations outside the specified permissible range of CT operating conditions and DB heat input rates can cause changes in operating temperature of pressure parts and DB parts that can lead to short-term failures in some components and considerably accelerate the life expenditure of pressure part components both upstream and downstream of the DB. This report recommends that DB are not operated outside the specified permissible range of CT operating conditions and DB heat input rates until a comprehensive thermodynamic analysis of the proposed changes to operation of the DB has been performed, and the impact of the consequential changes to gas temperatures and velocities, steam temperatures, and tube temperatures in all sections of the HPSH and RH have been thoroughly evaluated. DB operate effectively and reliably without excessive consequential damage to pressure parts and the DB, themselves, only in a relatively narrow specified range of CT exhaust conditions at the HRSG duct inlet. Primarily, these conditions are:

- Exhaust gas mass flow
- Gas velocity at the DB
- Exhaust gas distribution in the inlet duct
- Temperature
- Moisture content
- Oxygen content
- DB heat input

These conditions can also be affected by changes in compressor hardware, combustion-system hardware, turbine hardware, CT controls, CT load, and CT inlet-guide vane (IGV) position. Off-design operation in any of these conditions is likely to cause damage to downstream pressure parts, may cause damage to upstream pressure parts from DB induced attemperator over-spraying, may result in deteriorated emissions performance, and may damage DB components.

1.3 Roadmap Steps

This report provides a set of steps that can be used to avoid DB and HRSG design details that are known to have caused, or contributed to, premature component failure. These steps may also be used to detect and mitigate DB-related damage in existing units resulting from less-than-optimum design features and operating practices.

The remainder of Section 1 discusses the components that may be damaged by non-optimal DB design, operation, or maintenance, and the DB operating practices that are known to have produced this damage. Section 2 lists the procurement steps recommended to avoid in-service DB-influenced damage or to address incipient DB-influenced damage that has been detected in an existing, operating HRSG. Section 2 also lists the actions that should be taken throughout the life cycle of the HRSG to minimize the potential for DB-influenced damage. Section 3 discusses the specific design attributes that must be understood and controlled to avoid DB-influenced damage. Section 4 discusses the specific operation and maintenance practices that must be understood and controlled to avoid DB-influenced damage. Appendix A provides a comprehensive list of information that is useful to collect and assess, in order to avoid DB-influenced damage or to assess the root cause of active DB-influenced damage. Appendix B provides some case studies that illustrate DB-influenced damage or damage precursors, and steps taken to eliminate repeat occurrences of the damage or damage precursors.

1.4 Design Details of Concern

1.4.1 Failures Caused by Thermal-Mechanical Fatigue

The following HRSG and DB components have experienced premature distortions or thermally-induced fatigue failures due to improperly managed thermal expansion associated with DB design or operation:

- Exhaust gas turning vanes
- Cylindrical exhaust gas flow guides
- Perforated exhaust flow distribution plates
- DB runners and support structure
- DB and side-wall mounted exhaust gas baffles
- DB zone side-wall liner assembly
- Superheater/reheater tube-to-header connections
- Superheater/reheater headers
- Superheater/reheater support structure
- Superheater/reheater interconnecting piping

The following table illustrates the amount of thermal expansion that occurs during a 555 °C (1000 °F) increase in metal temperature:

Material	Strain	Elongation	Elongation
	in/in or mm/mm (%)	in/10 ft	mm/m
Carbon steel	0.8	0.97	8
T91	0.7	0.83	7
Austenitic Stainless steel	1.0	1.24	10

For typical tube-to-header or pipe-to-header connections, (which often have a combined global and local stress concentration factor approaching five or more), the nominal strain that will crack the protective surface oxide at the attachment weld toe and initiate fatigue damage is approximately 0.04%. This magnitude of strain occurs when the components have temperature gradients or tube-to-tube temperatures differences of about 22 °C (40 °F) for austenitic stainless steel, 28 °C (50 °F) for carbon steel or low chromium-molybdenum steels (Grade 11 or 22), and 31 °C (55 °F) for modified 9% chromium steel (Grade 91).

This illustrates the importance of ensuring uniform distribution across the duct of the DB heat to ensure nearly equal heat input to all tubes in the harp downstream of the DB, and also of flexible designs that do not restrict the differential expansions of the duct liner plates, burner elements, burner support structures, baffles, or downstream harp components, etc. For example, the repeated application of temperature maldistributions even as small as 20 °C to 30 °C (40 °F to 55 °F) in components that are connected to common headers or to each other may produce localized, irreversible fatigue damage with or without visible deformation or distortion of the components.

1.4.2 Failures Caused by Overheating of Components

Non-optimal DB design or operation has also produced damage during sustained periods of steady-state operation when the heating produced is excessive or non-uniform. The following HRSG and DB components have experienced premature failure due to overheating or excessive heat flux during sustained periods of operation with non-optimal DB conditions:

- Superheater tubes
- Reheater tubes
- Evaporator tubes
- DB flame holders
- DB firing zone casing liner plates and gas baffles
- Superheater/reheater tube support structures

For the materials commonly used to fabricate these components, a very modest increase in temperature of approximately 10 °C (18 °F) will double the rate of surface oxidation or creep-strain accumulation damage. Sustained periods of operation with even modest temperature maldistributions or excessive metal temperatures may lead to significant reductions in component life.

1.5 Operating Practices of Concern

The following operating practices are known to cause premature HRSG pressure parts damage or failures:

- Operation of DBs below CT full load in units not specifically designed to do so
- Operation of duct burners below the CT load range or above the DB heat input rate for which the HRSG and DB systems were designed
- Increases in DB firing rate that out-pace the consequential increase in superheater/reheater steam flow rates
- Operation with DB flames impinging on downstream tubes

1.6 Other Duct Burner Design Issues of Concern

- DB-induced HPSH or RH attemperator over-spraying down to saturation, causing severe metal quenching of downstream pipes and headers, and tube-to-tube temperature maldistributions during periods of DB operation below the CT load range or above the DB heat input rate for which the HRSG and DBs were designed
- Moisture accumulation, corrosion, and corrosion product buildup in the duct burner fuel pipes and pilots during periods of HRSG operation with the duct burners out of service
- Cold duct gas temperatures and duct burner flame instability in DB arrays located downstream of heat absorbing banks of tubes.
- Duct burner flame instability associated with the direction, and magnitude of the upstream gas velocity

1.7 Historical Perspective

Historically, DBs have been viewed as a relatively simple device that can deliver the increased unit output and operating flexibility with relatively low capital investment, low maintenance costs, and low risk of secondary-equipment damage with a nominal level of operations skill. This was largely the case for cogeneration and combined cycle plants equipped with aero-derivative and E-Class CTs, which have relatively benign exhaust gas temperature characteristics. However, the advent of the F-, G-, and H-Class advanced CTs, which have significantly higher, more challenging exhaust-gas temperatures and flow rates, has increased the DB and HRSG design complexity, increased the risk of catastrophic secondary-equipment damage, and increased the level of operations knowledge necessary for successful, reliable performance of DBs. It is critical for successful operation that the design of the DB system be carefully coordinated with the CT and HRSG designs and operating conditions. It is equally critical that the DB system be carefully commissioned, maintained, and operated strictly within its design parameters.

The exhaust gas characteristics of earlier CTs typically consisted of moderate mass flow, temperatures at or below 1050°F (565°C), moisture levels between 5 and 8%, and oxygen contents between 14 and 15% by volume-wet. In contrast, advanced CTs with their dry-low NO_x combustion systems produce exhaust gas with higher mass flow (because of their larger engines), higher temperature, lower oxygen content (because of their higher engine efficiencies and modulated IGVs), and higher moisture content (because they have higher firing rates converting more fuel-bound hydrogen to water vapor). CT exhaust gas moisture levels of 10 to 17% are not uncommon for F-Class CTs; they can approach 25% with heavy steam injection for power augmentation

2
ROADMAP APPROACH

2.1 General Steps for Avoiding Pressure Part Damage Caused by Duct Burners

The HRSG design, DB design, and the plant operating procedures must be carefully coordinated if pressure part damage is to be reliably avoided. Procurement of such a DB system is performed in the steps shown in Column 1 of Table 2-1. Assessing and correcting DB-related pressure part damage in existing units is performed in the steps shown in Column 2 of Table 2-1.

Table 2-1
Roadmap Approach for Procurement of Duct Burners and for Assessing and Correcting Pressure Part Damage

Procurement steps to avoid in-service DB-influenced damage	Steps for assessing DB-influenced damage in existing HRSGs
Step 1 - Owner to specify that HRSG, DB and control system design features and operating practices known to contribute to pressure part failures are not acceptable. Owner to specify detailed scope for comprehensive thermodynamic analysis over the required full range of DB operation and demonstrate the mechanical compatibility of the design of HRSG components and DB system with the results from the thermodynamic analysis of gas, steam and component operating conditions during DB operation.	Step 1 - Collect and review background and plant historian data. Perform comprehensive thermodynamic analysis for DB operation outside the range for which it was originally designed and assess the mechanical compatibility of the design of HRSG components and DB system with the results from the thermodynamic analysis of gas, steam and component operating conditions during DB operation.
Step 2 - Owner to review proposed detailed design and operating procedures for HRSG and DB prior to contract award to ensure compliance with Step 1.	Step 2 - Evaluate HRSG/DB configuration, instrumentation, controls, operation practices, maintenance practices, unit condition and historical data for risk of DB induced damage.
Step 3 - Owner to specify the design and manufacture/fabrication requirements of special damage monitoring instrumentation and operating tests to be performed during commissioning.	Step 3 - Specify the design and manufacture/fabrication requirements of special damage monitoring instrumentation and operating tests to be performed.
Step 4 - Owner to specify damage monitoring instrumentation, controls, data acquisition systems and data evaluation methods to be used to monitor DB related component damage throughout the lifetime of the HRSG.	Step 4 - Identify any HRSG or DB components exposed to off-design operation via operational testing.

Table 2-1 (continued)
Roadmap Approach for Procurement of Duct Burners and for Assessing and Correcting Pressure Part Damage

Procurement steps to avoid in-service DB-influenced damage	Steps for assessing DB-influenced damage in existing HRSGs
Step 5 - Owner to facilitate sufficient and timely quality control inspections during fabrication and erection to ensure installed equipment, control logic and operating procedures meet design requirements.	Step 5 - Using the results from the thermodynamic analysis of gas and steam conditions throughout the planned range of DB operation determine the physical modifications or operating procedure changes necessary to avoid damage during off-design operation.
Step 6 - Identify any HRSG or DB components exposed to off-design operation via operational testing during commissioning.	Step 6 - Verify, through additional diagnostic/troubleshooting, monitoring, thermodynamic modeling and unit operation, that the alterations or corrective actions have been successful.
Step 7 - Determine the physical modifications or operating procedure changes necessary to avoid damage during off-design operation.	Step 7 - Specify damage monitoring instrumentation, controls, data acquisition systems and data evaluation methods to be used to monitor DB related component damage throughout the lifetime of the HRSG.
Step 7 - Verify, through additional diagnostic/troubleshooting monitoring and unit operation, that the alterations or corrective actions have been successful.	

2.2 Life Cycle Actions to Prevent Pressure Part Damage Caused by Duct Burners

Thermal-mechanical fatigue damage, accelerated creep damage, accelerated thermal aging (overheating), and under-deposit corrosion of pressure parts downstream of duct burners is cumulative and generally irreversible, hence these damage mechanisms must be detected and minimized early in the HRSGs life and periodically thereafter if nominal expected component lives and reliability are to be obtained. While most of these damage mechanisms require months or years to progress to failure, severe overheating resulting in failure within a matter of hours is possible in pressure parts downstream of duct burners. These damage mechanisms can be enabled by global or localized exhaust gas temperatures in excess of those anticipated by the designer as well as unintended aberrations in exhaust gas mass flow, exhaust gas velocity and steam mass flow. These adverse operating conditions may be caused either by equipment design deficiencies, or by operating practices or both.

Avoiding DB related pressure-part failure requires diligence throughout all life cycle stages of the HRSG. Some of the key actions required to prevent this damage are documented in the following roadmaps (Tables 2-2, 2-3 and 2-4, and Figure 2-1). The basis for these recommendations is provided in Section 3: Design Issues and in Section 4: Operation and Maintenance Issues, respectively.

Table 2-2
Development of Owner Specification for Duct Burners

Owner Specification
1. Define the range of CT loads at which the DB will operate and the maximum DB heat input as a function of CT load over the defined range of CT loads. See Section 3.2 Key HRSG Design Issues Related to Duct Burners.
2. Define the annual and lifetime operating regime and numbers of thermal cycles for the DB (staged runners, DB start stop cycles per year, seasonal DB layup periods with CT operating, etc.). See Section 3.1.4 Other HRSG Design Issues Related to Duct Burners.
3. Specify the minimum permissible degree of superheat in the attemperator outlet fluid temperature and the maximum HRSG HPSH and RH outlet steam temperature excursion above rated steam temperature. See Section 3.2.1 Influence of DB Capacity and Permissible Range of CT Loads During DB Operation on Attemperators.
4. Specify top-to-bottom and side-to-side gas- and tube temperature distribution downstream of DB. See Section 3.2.2 Other HRSG Design Issues Related to Duct Burners.
5. Specify active control of DB fuel manifold pressure. See Section 3.1.4 Other important Duct Burner Design Issues.
6. Specify low point drains for DB fuel gas manifolds with automatic DB pre-light-off blowdown. See Section 3.1.4 Other important Duct Burner Design Issues.
7. Specify automatic isolation valves on each runner at their HRSG casing penetration. See Section 3.1.4 Other important Duct Burner Design Issues.
8. Specify DB flame observation ports be provided in sufficient numbers and accessible locations to facilitate frequent visual observation of all DB flames.
9. Specify what special DB-related damage monitoring instrumentation is required. See Appendix C Damage Monitoring Systems.
10. Specify special DB-related damage monitoring tests and acceptance criteria to be performed during commissioning. See Appendix C Damage Monitoring Systems.
11. Specify damage monitoring instrumentation, controls, data acquisition systems and data evaluation methods to be used to monitor DB related component damage throughout the lifetime of the HRSG. See Appendix C Damage Monitoring Systems.

Table 2-3
Development of Design and Construction for Duct Burners

Design
1. Owner to review proposed HRSG, DB, and control system design and operating practices to ensure that features known to contribute to pressure part failures have been rejected. Examples include ineffective exhaust gas flow control at DB inlet, non-uniform DB fuel-gas distribution, DB-influenced overspray of attemperators, and operation of DBs at firing rates and CT loads outside of design combinations and ranges. See Section 3 Design Issues.
2. If uncooled flow distribution devices are used upstream of DBs, ensure that their design has been proven to withstand the range of anticipated temperatures at all loads and anticipated transients.
3. Require consideration of the impact on DB exhaust gas inlet conditions due to temperature changes in upstream heating surface. Require evaluation of flame length, flame temperature, and emissions versus exit gas temperatures from heating surfaces upstream of the DB throughout the unit's and DB's normal operating ranges as well as reasonably anticipated off-design transient conditions. The foregoing evaluations should be based on thermodynamic analysis to determine gas and steam conditions upstream as well as downstream of DBs.
4. Ensure that the boundary conditions and range of validity of CFD or small-scale modeling used to equalize exhaust gas flow into the DB are sufficient to accurately predict exhaust characteristics at the DB inlet while taking into account the variables listed in Section 1.2. See Section 3.1.1 Uniform distribution of exhaust gas flow at DB inlet.
5. Require both HRSG and also attemperator OEM evaluation of attemperator outlet conditions and final steam conditions (margin to saturation, outlet temperature) under stable operation at various conditions throughout the CT and DB operating range, and during dynamic conditions during CT/HRSG startups and shutdowns and other predictable major transient conditions.
6. For units intended to operate the DB at less than CT full load, require evaluation of flame length, flame temperature and emissions versus exit gas temperatures from heating surfaces upstream of the DB throughout the unit's and DB's intended operating ranges as well as reasonably anticipated off-design transient conditions.
7. For units intended to operate the DB at less than CT full load, require evaluation of upstream flow devices (guide vanes, cylindrical flow guides, perforated plates, heating surfaces, etc.) for impact on CT backpressure throughout the unit's and DBs intended operating ranges.
Construction
1. Facilitate sufficient and timely quality control inspections during fabrication and erection to ensure that installed equipment, control logic, and operating procedures meet design requirements.

Table 2-4
Development of Commissioning, Operation and Maintenance of Duct Burners

Commissioning
1. Identify any HRSG or DB components exposed to off-design operation via operational testing during commissioning.
2. Determine the physical modifications and operating procedure changes necessary to avoid off-design operation.
3. Verify, through additional diagnostic/troubleshooting monitoring and unit operation, that the alterations or corrective actions have been successful. See Appendix C: Monitoring Systems.
Operation
1. Ensure unit operating instructions unambiguously specify the range of CT loads and maximum permissible DB heat inputs versus CT load.
2. Require operators to frequently visually observe all DB flames, document flame characteristics and take immediate corrective action if flame impingement is noted.
3. Routinely review damage monitoring system data, operator flame observation and plant historian data.
4. Identify any HRSG or DB components exposed to off-design operation via data review and operational testing.
Maintenance
1. Maintain DB flame view ports in good working order at all times.
2. Perform annual visual and non-destructive evaluation (NDE) inspections of upstream flow devices, DB gas side components, downstream pressure parts, gas baffles, and duct liner systems.
3. Determine root cause of cracking, distortion, burning, etc. and take timely corrective action.

2.3 Periodic Condition Assessment of HRSG Pressure Part Damage Attributable to Duct Burners

The frequency of reported pressure part failures associated with DB operation indicates that many existing combined cycle units experience unanticipated off-design operation during steady-state and transient operating conditions. Many of these units may not yet have experienced pressure part failures if the off-design conditions are not too severe. However, they may expect premature pressure part failures well before nominal design life is reached. Some of the key actions required to assess the likelihood of this damage are documented in the following roadmap (Figure 2-1).

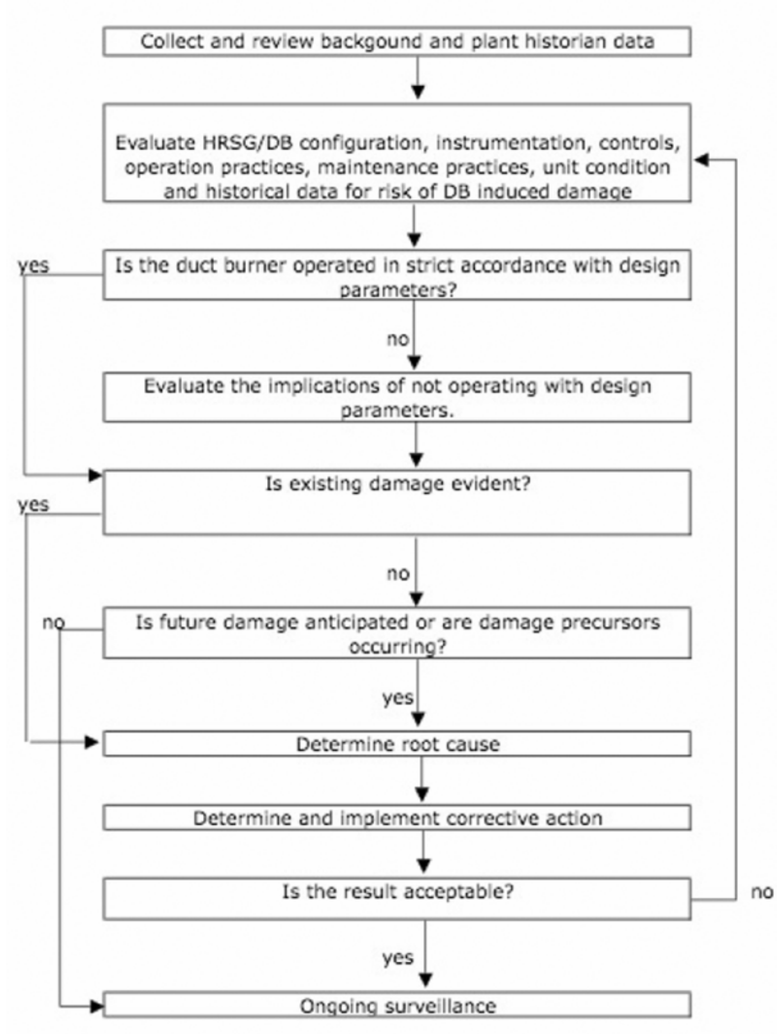

Figure 2-1
Roadmap for Optimizing Duct Burner Operation and Maintenance to Avoid Pressure Part Damage

3
DESIGN ISSUES

3.1 Key Duct Burner Design Issues

3.1.1 Uniform Distribution of Exhaust Gas Flow at DB Inlet

For the duct burner to perform properly, the exhaust gas and fuel must be evenly distributed across the burner array. This ensures that the fuel mixtures and gas velocities needed for flame stability and complete combustion are consistently attained at each burner nozzle. Only in this way can relatively uniform and predictable DB exit gas temperatures be attained. All CTs produce exhaust gas of swirling, turbulent, and velocity-stratified patterns. These patterns change not only with engine model but also with CT load and ambient conditions. In addition, the size and approach angle of the CT-to-HRSG transition duct can have a profound effect on exhaust gas distribution into the DB array, even on those HRSGs with the DBs positioned in the direction of gas flow behind the secondary HPSH and RH sections and before the primary HPSH and RH sections. (Figure 1-5)

Often, it is necessary to install some form of flow straightening, velocity-equalizing exhaust gas control device upstream of, or within, the DB array. Common elements of these devices include perforated plates, fixed guide vanes, cylindrical flow guides, baffle assemblies, and HRSG heat transfer surfaces (generally HPSH and RH tubes). These devices may be used alone or in combination (Figures 1-3 through 1-5).

Computational Fluid Dynamics (CFD) and scale model testing are typically used to design these flow manipulation devices. Unfortunately, the addition of flow manipulation devices results in additional backpressure with resultant reduction in CT output and efficiency. If the device consists of large uncooled guide vanes or cylindrical structures, they often suffer from severe cracking and prove unreliable—especially when they are used with advanced CTs that operate with significantly higher exhaust gas temperature—and also require much wider HRSG ducts to handle the substantially larger CT exhaust gas flows. In this respect, guide vanes in HRSGs behind 50-Hz CTs must span even wider ducts than the 60-HZ equivalent CT, which has 70% of the exhaust gas flow. DB flow baffles, located between the runners, may break loose from the wall if there is insufficient room for thermal expansion or if liner plates are loose and able to vibrate. Older units equipped with unreliable guide vanes or cylindrical flow guides may find that an evaluation of their design making use of advances in DB technology can reduce or eliminate the need for these devices.

In the case of DBs operating in the low oxygen exhaust gas typical of newer, large CTs, it is important to consider all of the variables referenced in Section 1.2. With these units, well executed CFD analysis using a validated model is required. This is a major change from older HRSGs, where ambient temperature small scale flow modeling was sufficient to predict DB behavior. Unfortunately, many HRSG and DB systems are installed without adequate validation of the CFD model. As with any design model (FEA, etc), accurate prediction of DB performance in new units using CFD analysis requires that the boundary conditions selected reasonably reflect the actual conditions to be experienced by the equipment or system. Often, this is easier said than done.

To be effective, such modeling should be conducted by someone with experience in performing this work on HRSGs. The owner should question the OEM as to how the CFD model to be used has be validated for the particular model of CT and design of HRSG proposed. A credible verification will likely require temperature traverses in an existing HRSG of similar design and CT model across the width and height of the duct, both upstream and downstream of the DB. The CFD modeling should include calculating the sensitivity of results to variations in exhaust gas characteristics, to which the DB is known to be sensitive and which experience has shown may reasonably be expected.

3.1.2 Uniform Distribution of Fuel Gas Flow to Each Fuel Nozzle in the DB Array

To achieve uniform fuel gas flow distribution throughout the DB array, it is necessary to install fuel balance valves on each runner, and to individually size the orifice at each fuel nozzle. The orifices are generally arranged with progressively larger orifices on fuel nozzles more distant from the runner's casing penetration (fuel supply end). Proper trimming of these valves and orifices compensates for differences in piping and runner internal flow losses, as well as for top-to-bottom and side-to-side variations in CT exhaust gas mass flow distribution at the DB inlet. This balancing is necessary if reasonably uniform gas temperature distribution and DB flame lengths are to be attained at the DB exit.

3.1.3 Influence of Exhaust Gas Temperature at the DB Inlet on DB Reliability and Performance

The practice of placing heat transfer surface upstream of the DB as a flow manipulation device has the advantage of not incrementally adding to CT backpressure—as would be the case if separate flow distribution devices were employed. However, since the heat transfer surface upstream of the DBs significantly cools the CT exhaust gas prior to it reaching the DB, this approach must be tempered in order to maintain gas temperature at the DB inlet above the minimum required for acceptable and reliable DB operation.

When the DB are in operation, increasing the DB heat input causes an increase in the gas mass flow and temperature through the HP evaporator, thus it increases HP evaporation rate and HPSH steam flow. The increase in DB heat input also increases the heat transferred to steam in the primary HPSH. As a result, the outlet temperature from the primary HPSH is likely to be increased, which in turn requires that additional attemperation water be sprayed in order to limit the steam temperature at the outlet of the secondary HPSH.

Although the gas flow rate through the secondary HPSH and RH upstream of the DB is unchanged, the heat transfer rate in the HPSH and RH will be higher because the mass flow—thus steam velocities—through the HPSH and RH tubes is higher. This results in a lower gas temperature at the DB inlet. Thermodynamic analysis is required to establish the changes in gas and steam flows, pressures, and temperatures resulting at the DB inlet and in the various heat transfer modules. For best results, the thermodynamic model must adjust the heat transfer coefficients in each section of the HPSH and RH, to accurately account for the changes in gas-side and steam-side flow rate.

Variations in gas temperature upstream of the DB due to variations in the operating performance of upstream heat-transfer surface that are a consequence of the impact of DB heat input on the downstream surfaces may alter DB performance with the following consequences:

- Higher gas temperature at the inlet to the DBs enhances DB flame stability and helps ensure complete combustion
- DB flames begin to quench in exhaust gas below 700 °F (371 °C)
- Lower DB flame temperature (from quenching) results in lower NO_x, but higher CO and unburned hydrocarbon
- Higher DB flame temperature results in higher NO_x, but lower CO and unburned hydrocarbon

3.1.4 Other Important DB Design Issues

In some units, CT exhaust gas velocity at full load can attain 3000 ft/min (0.9 km/min). This is equivalent to a 34 mph (55 km/hr) wind with significant turbulence, spiraling flow, and eddies. For the DB to perform effectively under these conditions, the velocity profile into the burner should be ±25% of the average free-stream velocity with the velocity vector perpendicular to the burner plates. The free-stream velocity is critical to the design and performance of the DB baffles and array.

As noted in Section 1.7, exhaust gas moisture levels can range from 5 to 25%. In older CTs that produce exhaust gas with relatively high oxygen content and stable mass flow, variations in moisture level have only a modest effect on DB flame length. However, high efficiency CTs, particularly those equipped with dry-low NO_x combustion systems, produce exhaust gas with much lower oxygen content and variable mass flow relative to fuel burned. The impact of moisture and mass flow levels on DB flame length in the lower oxygen environment is much greater than is experienced with the older model CTs. Therefore, great care is needed during the design, commissioning, and operation of DB-equipped units using today’s high efficiency, low emissions CTs.

When DB are not being fired, but the CT is, CT exhaust gas will enter the DB fuel piping through the non-firing DB nozzles, and condense inside the cooler external runs of the DB fuel piping. Given the high exhaust gas moisture levels noted above, this can result in significant quantities of condensate formation in external DB piping. The condensate—which is acidic—corrodes the inside of the piping and damages valves, which in turn leads to clogged fuel nozzles, fouled igniters, and unreliable DB performance. This can be prevented by the installation of remotely operated, and preferably automatic, isolation valves on each fuel runner where it enters the HRSG casing. Alternatively a blower may be used to constantly pressurize the DB fuel system above the gas pressure in the duct whenever the DB are not being fired. However, the energy consumption of a fan of sufficient capacity to do this job without isolation valves can be high. Some operators configure their duct burners with both, allowing the fan to be much smaller. It is also good practice to install automatic drain valves at fuel manifold low points, and cycle these drains via the DB burner management system prior to DB light off. This enhances light-off reliability by removing any accumulated condensate before it can interfere with igniter or main flame performance.

To prevent DB over-firing, NFPA 85 mandates a DB trip when excessive DB fuel-pressure conditions occur. Some operators have installed a pressure transmitter on the main DB fuel header as feedback to the DCS to back off DB fuel flow when one or more runners is isolated or tripped. This scheme can prevent high gas pressure trips and have the added important benefit of lowering the risk of flame impingement. It is recommended that plants lacking this feature should consider its retrofit.

3.2 Key HRSG Design Issues Related to Duct Burners

Some HRSG designs allow steam production to be doubled via the addition of duct burners with no significant changes to pressure parts. In these HRSGs, tube fin length must be designed to limit the fin metal temperature. Other HRSGs are designed to operate with higher pressures during duct burner operation; hence they require thicker pressure parts. HRSGs with a thick HP drum and HPSH headers will require longer startup times, are generally not suitable for cycling service, and may present a challenge in attaining design fatigue life of the heavier components even if operated with few start/stop cycles.

To help the OEM produce a design that better matches the anticipated operating profile of the unit, the owner should define the range of CT loads in which the DB will operate and the maximum DB heat input as a function of CT load over that defined range. If the DB will be used only to augment power production at full CT loads, the designer's job is much simpler. In fact this is likely to be the default design case if no additional detail is provided by the owner. On the other hand, if the owner wishes to use the DB to increase unit output during the CT's ramp-up to full load, then both the HRSG and the DB designs become more challenging. Specific details about the combinations of DB firing rate that correspond to various CT loads will be needed. Such information might be communicated via a curve with zero DB firing below 60% CT load, a maximum DB firing rate of 50% between 60% and 70% CT load, etc. Any DB firing below full CT load requires careful coordination of the DB and HRSG design. Aggressive DB firing below full CT load comes at the cost of more complex design analyses, higher equipment cost, and greater risk of pressure part damage.

3.2.1 Influence of DB Capacity and Permissible Range of CT Loads during DB Operation on Attemperators

HRSGs equipped with large capacity duct burners (>500 MMBtu/hour, or 160 MW) require more complex attemperator systems with greater attemperation turndown capability. This is due to the large range of attemperator spray flow required for fired versus unfired conditions.

The larger spray water flow associated with higher DB heat input rates, or with HRSGs designed to operate with DB over a wider range of CT loads, significantly increases the likelihood of operating at times with gross overspray conditions at the attemperator outlet. This is especially true under certain dynamic load change conditions and if the CT is a GE F- or H-class gas turbine. These models develop maximum exhaust gas temperature at CT generator loads between 30% and 60% when HPSH and RH steam flows are well below maximum. Two stages of interstage attemperation—with one attemperator positioned between the primary and intermediate HPSH, and the second positioned between the intermediate and final HPSH—may be required in order to avoid spraying too close to saturation while also avoiding exceeding the design outlet steam temperature of the superheaters. A similar, two-stage arrangement may be required in the reheaters of these units. In addition, simple temperature control loops are not adequate for use with large capacity duct burners. More sophisticated, multilevel, anticipatory control systems are required.

3.2.2 Other HRSG Design Issues

The owner should specify that superheater and reheater attemperators be capable of maintaining a minimum of 50 °F superheat at the attemperator outlet without superheater/reheater outlet steam temperatures exceeding their respective design temperature. This requirement should apply to all CT loads, CT loading rates, DB firing rates, DB staging, and DB firing ramp rates that the unit is intended to encounter. A 50 °F margin to saturated conditions at the attemperator outlet should prevent quenching of downstream piping and pressure parts when moderate unanticipated transients or errors in design calculations occur. The HRSG OEM should be required to verify that the design complies with this requirement via dynamic modeling.

Frequent cycling of units equipped with duct burners results in more thermal expansion related wear, as well as distortion of DB support structures and displacing of parts—such as runner and support guides, expansion sleeves, and casing penetrations. Routine visual inspection of these components is recommended. Units that operate the CT at base load while heavily cycling their duct burners may expose HRSG pressure parts to additional thermal fatigue and creep (see discussion below on DB firing rate control).

While the specific temperature profile must be determined on a case-by-case basis, the exhaust-gas temperatures entering the heating surface downstream of the DB should be relatively uniform (+/– 100 °F of average exhaust gas temperature) if the key elements of DB and HRSG design and the exhaust gas characteristics at the DB inlet reasonably match the designer's assumptions. Since this is often not the case, the owner should require the HRSG OEM to state the maximum side-to-side and top-to-bottom exhaust gas temperature differences to be guaranteed at the face of the first row of tubes downstream of the DB. On the basis of these values, the HRSG OEM can then design for the maximum tube metal temperatures for this heating coil. The owner should instrument the downstream coil and verify with operational testing during commissioning that actual exhaust gas temperatures and metal temperatures are within the predicted values. See Appendix C: Damage Monitoring Systems.

4
OPERATION AND MAINTENANCE ISSUES

4.1 Operational Issues Affecting All HRSGs with Duct Burners

Unfired HRSGs are relatively immune to short-term overheating of pressure parts unless they are operated well outside OEM guidelines. However, the inclusion into the design of an HRSG of any class and size of supplemental firing introduces the potential for rapid and catastrophic short-term overheating damage. CTs produce exhaust temperatures between 900 °F and 1200 °F (482–650 °C). Typical duct burners produce design firing temperatures between 1200 °F and 1470 °F (650–799 °C), and may even reach 1600 °F (871 °C) when design values are complied with for exhaust gas mass flow, temperature, and velocity into the burner, as well as for DB fuel flow, quality, and distribution. Even moderate changes in any of these variables can result in higher-than-design firing temperatures and flame impingement on downstream structures and pressure parts. Likewise, sufficient mass flow and uniform distribution of steam in the superheater and reheater modules downstream of the DB are required, in order to prevent over heating these pressure parts.

During severe conditions, catastrophic short-term overheating damage to duct burner equipment, pressure parts, and structures can occur in a matter of hours. In general, higher DB firing rates result in longer DB flames and increased risk of flame impingement. Off-design operation, failure of exhaust flow distribution devices, or other changes that affect the exhaust profile into the duct burners can also result in flame impingement. Careful commissioning, maintenance, and operation are required to minimize the risk—and allow early detection—of flame impingement.

Most DB-equipped HRSGs have a number of inspection ports installed in the casing to allow visual inspection of DB hardware and flames while the unit is in-service. It is important to maintain these inspection ports in good condition and use them frequently to inspect all flames from a variety of angles. Any change in flame color, shape, or size should be investigated immediately.

DBs operating at high firing rates behind advanced CTs often produce “wisps” of flame that float downstream and then burn out. These can be confused with flame impingement during visual observation. Wisp impingement is less severe than true flame impingement, but it should also be avoided. A wisp is a hotter bubble of gas and will result in increased creep rate in downstream pressure parts. If wisps are observed, consideration should be given to reducing DB firing rate so that they are eliminated. Continuous flame impingement on pressure parts will increase their creep rate much faster than wisps, potentially leading to creep rupture failures in hours rather than weeks. Continuous flame impingement, as opposed to wisps, will be accompanied by an increase in CO and unburned hydrocarbons as the DB flame is quenched by contact with tubes or structure. An increase in DB firing rate can produce dramatic increases in a plant's carbon monoxide emissions—perhaps hundreds or even thousands ppm CO, depending on the firing rate and the contribution of CO from the CT exhaust. Given the magnitude of these potential increases, owners with high firing-rate DBs should use on-line CO monitoring as an early indication of flame impingement. A baseline CO reading can be established against which to compare during ongoing operation. If the DB can be operated at 100% firing rate without impingement the baseline value should be determined at this point. If this is not possible, the baseline value should be determined at a lower DB firing rate where visual observations confirm no impingement is occurring. If DBs are to be operated at CT loads less than 100%, DB CO contribution baseline values should be established throughout the CT load range where the DB is to be fired.

Flame impingement is not the only mechanism by which over-temperature damage can be inflicted on HRSG pressure parts. Over-temperature operation can occur, for hours rather than minutes, in primary HPSH and RH sections and HP evaporator tubes when DB heat input is increased too quickly. When DB heat input is ramped up and the steam turbine is operating in sliding pressure mode with HP inlet valves wide open, then there is a significant time lag before HP steam flow increases and even more so before RH steam flow increases. Increasing the DB heat input raises both the gas temperature and the mass flow into the downstream sections of the primary HPSH and RH sections as well as into the HP evaporator. The higher gas temperature immediately increases the metal temperature of the downstream primary HPSH and RH tubes. When the DB heat input is raised quickly and the steam turbine is operating in sliding pressure control mode with the HP valves wide open, then the increase in HP evaporation is initially utilized to raise HP steam pressure. HP steam flow to the steam turbine can only increase as the HP pressure rises. Until higher HPSH and RH steam flows develop, there is a significant increase in temperature rise through the primary HPSH and RH sections.

The inevitable consequence of higher gas-side and steam-side temperatures is significantly higher tube metal temperature. The higher steam temperatures also raise the header and interconnecting pipe temperatures. Furthermore, the steam temperature at inlet to the interstage attemperators is significantly higher, requiring increased attemperation water, which significantly increases the risk of overspraying down to saturation.

To minimize these damaging conditions, DB firing ramp rates must be coordinated with the time lag in and the magnitude of increase in steam production. Proper coordination will ensure that the temperatures of primary HPSH and RH tubes, headers, and pipes do not exceed their design limits, and also will prevent potentially severe damage to pipes, headers, and tubes downstream of the attemperators from overspraying. Tube temperature measurements at judiciously selected tube locations are recommended to optimize DB controls for maximum ramp rate while avoiding pressure part damage.

Some operators have programmed their DCS with algorithms that set DB fuel flow to predicted levels for the target MW increase. They then trim to the MW setpoint after their unit has stabilized. This practice is NOT recommended, because it does NOT reliably prevent overheating.

Uncontrolled—hence potentially damaging—DB ramp rates increase load in the range of 7.5 MW/min to 14 MW. In contrast, properly coordinated DB ramp rates will increase load at 2 MW/min to 4 MW/min. One operator reports that two hours are required to safely ramp the DB to its maximum heat input, in order to avoid excessive HPSH tube metal temperatures and attemperator overspray. This unit is equipped with a 550-MMBTU/hr (160 MW) DB.

4.2 Operation of Duct Burners Below CT Full Load

A surprising number of combined cycle plant operators place—or are considering placing—their duct burners in service when the CT is less than fully loaded. Perhaps they have come up with this potentially very damaging concept from colleagues in the cogeneration industry, where many plants have been specifically designed to operate this way. For a cogen plant, this capability usually was incorporated into the original design (by designing key pressure parts for higher metal temperatures and higher volumetric steam flow rates, and appropriately positioning attemperators within the HPSH and RH surfaces) to ensure that the host's steam demand can be met independently of CT load. However, most power production combined cycle plants are designed for lowest cost, maximum electric output and minimum heat rate. These goals generally preclude a design capable of DB operation at less than full CT load.

Only units specifically designed and built for operation of the DB at less than full CT load can do so without risk of severe DB and HRSG damage!

Even specially designed units can successfully operate the DB only within a specified window of CT load and DB load. Before operating outside the original specified window for DB operation, it is strongly recommended that a comprehensive thermodynamic analysis is performed to establish gas and steam conditions under steady-state conditions for the proposed modified operating window with DBs and under dynamic conditions during ramping up of DB heat input to assess the compatibility of the predicted modified operation conditions with the design limits of the installed pressure part components.

Some of the major design concerns when configuring a plant to operate the DB with the CT at lower loads include exhaust gas flow distribution device design, duct burner configuration, tube metal temperatures, radiant heating effects, attemperator design, and LP evaporator flow regimes.

When CT load or IGV openings are reduced, exhaust gas mass flow into the DB also is reduced. Lower mass flow results in less mixing of energy at the DB, hence greater fuel burnout time and longer flame length. In general, operation at lower CT loads or reduced CT IGV openings results in:

- Increased swirl effect in the exhaust gas, leading to localized changes in exhaust gas mass flow, exhaust gas flow direction, exhaust gas temperature at the DB inlet, and DB fuel-to-exhaust-gas ratio.
- Reduced exhaust gas mass flow, leading to redistribution of exhaust gas flow through flow control devices and tube bundles. In tall, steeply angled HRSG inlet ducts, this often results in less exhaust gas reaching the DB at upper elevations.
- A change in the exhaust gas temperature into the DB (whether higher or lower depends upon the CT model and its combustion system).

Symptoms resulting from these changes can include:

- Greatly increased risk of flame impingement on downstream pressure parts, sidewalls, and structures.
- Reduced effectiveness of upstream flow control devices. (Note: Exhaust gas flow control devices configured for low CT load operation of DB generally produce higher CT backpressure and performance loss at full CT load.)
- Longer visible DB flames
- Altered emissions performance.

Duct burner operation with the CT at less than full load is not recommended, except for units specifically designed to do so, where a thorough thermodynamic and mechanical analysis of steady-state and dynamic conditions relative to DB operation has been conducted, an on-line pressure part damage monitoring system is in service, and data from the monitoring system is frequently reviewed by a qualified person.

4.3 Impact of Duct Burners on Chemistry

DB operation also can impact the unit's steam and water chemistry. For example, steam carryover can be caused by feedwater flow instability, which can stem from DB firing. This occurs when a sudden increase in DB heat input causes a significant increase in steam volume in HP evaporator tubes and drum swell, which initiates flow instability in poorly configured, maintained, or tuned feedwater systems. In addition, DB operation can aggravate phosphate hideout, giving a higher risk of acid phosphate corrosion if the HP evaporator is operated with any acidic phosphates (mono- or di- sodium phosphate) or blended mixtures that contain an acid phosphate. Caustic treatment or Phosphate Continuum (PC) are better choices for a unit with DB, since caustic does not exhibit decreasing solubility at increasing fluid temperature and tri-sodium phosphate hideout will not produce a corrosive environment under any deposits.

If DB-nozzle fuel flows have not been balanced by tuning orifices at each burner nozzle to achieve uniform temperature distribution, then tube samples should be routinely analyzed to establish a proper chemical cleaning interval. Tube samples should be analyzed for both the quantity and the composition of their internal deposits. Samples should be removed from the hottest HP evaporator tubes—usually near the DB gas inlet sidewall if the DB nozzle openings have not been adjusted to compensate for the pressure drop along the length of the DB runner fuel pipe. This location will generally have higher DB fuel gas pressure and fuel flow; hence it will produce higher heat flux and associated waterside deposit loading rates.

A INFORMATION NEEDED TO ASSESS AND AVOID DB-INFLUENCED PRESSURE PART DAMAGE

This appendix lists typical information that should be collected (Section A.1) and the evaluations that should be performed (Section A.2) to determine if DB influenced damage or damage precursors are active or to help determine the root cause of incipient damage.

A.1 Collection and Review of Background and Plant Historian Data

HRSG and DB Attributes

To begin the assessment process, unit-specific information on HRSG and DB equipment configuration and design details must be assembled. It is important to determine such design assumptions and limits as maximum permissible metal temperature, maximum permissible temperature difference between components, and maximum anticipated thermal expansions. Sources for this information are OEM equipment manuals and drawings; A/E documents and drawings, construction and commissioning records; the memories of key people involved in plant design, construction, commissioning, operation and maintenance; and visual inspection of equipment. Listed below are some of the details to be assembled regarding HRSG and DB configuration:

- Dimensional and arrangement drawings of uncooled upstream flow devices:
  - Perforated plate
  - Guide vanes
  - Cylindrical flow guides
- Dimensional and arrangement details of upstream and downstream heating surfaces of:
  - HP Superheater
  - Reheater
- Superheater and reheater attemperators
  - Single interstage
  - Multiple series interstage
  - Location of attemperator(s) relative to superheater/reheater inlet (steam drum/cold reheat) and outlet (main steam/hot reheat)

- DB fuel system
  - Details of DB nozzle orifices for side-to-side fuel flow balance
  - Details of DB runner valves/orifices for top-to-bottom fuel flow balance
  - Details of DB runner automatic isolation valves
  - Details of DB fuel system automatic condensate drains
- DB flame view ports
  - Are there sufficient numbers
  - Are the locations effective

Instrumentation

Unit-specific descriptions of available instrumentation—including precise locations of sensors for determination of DB-related temperatures and pressures during all operating modes and transients—also are needed. Listed below is some of the instrumentation that may be of use:

- DB fuel manifold pressure feedback to burner control
- Duct gas temperature sensor array upstream of DB
  - Location (top to bottom and side to side)
  - Number and type of temperature sensors
- Duct gas temperature sensor array downstream of DB
  - Location (top to bottom and side to side)
  - Number and type of temperature sensors
- Superheater/reheater tube metal thermocouple array downstream of DB
  - Location (top to bottom and side to side)
  - Number of thermocouples and details of type and method of attachment to tubes, details of insulation from influence by gas temperature or radiation

Controls

Unit-specific descriptions of DB related control logic, control devices and control performance for all operating modes and transient conditions also are needed. Listed below are some of the control features of importance:

- Sophistication and effectiveness of attemperator control
  - Avoid attemperator overspray
  - Avoid excessive steam outlet temperature
  - Avoid severe tube-to-tube metal temperature maldistributions

- DB firing ramp rate automatically limited
  - Based upon downstream tube metal temperature
  - Based upon SH/RH steam flow lag
  - Based upon preset limits
- Coordination between the CT exhaust gas conditions, steam temperature and DB controls
  - Maintain adequate exhaust temperature into DB when there is upstream HPSH and RH surface

Operating Practices

- Unit-specific information regarding intended and actual operation practices/procedures also is needed. Listed below are some important considerations:
- Operators provided with clear, unambiguous specification of the permissible range of CT loads and duct burner heat inputs during DB operation?
- DB fired at less than full CT load or outside the specified range of CT loads/ maximum DB heat input limits?
- DB flames routinely observed/documented
- Procedures for flame impingement corrective action in place and followed
- Historical DB firing ramp rate
- Evidence of steam drum carryover
- Historical emissions data

Maintenance and Inspection

Unit specific information regarding DB-related maintenance procedures and equipment condition also is needed. Recent outage inspection results for DB related equipment and HRSG pressure parts are also necessary. Listed below are some items to be considered:

- Condition of DB in-duct components and support structure
  - Sagging
  - Misalignment
  - Burning
  - Missing parts

- Condition of downstream components
  - Superheater/Reheater
    - Longterm overheating
    - Short term overheating
    - Thick or exfoliated oxide scale
    - Distortion
      - Tubes
      - Tube support structures/gas baffles
      - Headers
  - Evaporator
    - Waterside deposits
    - Gas side appearance
  - Burner duct liner, refractory, insulation and casing
- DB flame view ports
  - Lenses clean
  - Lens dampers and return springs/counter weights operable
  - Insulated handles in place
  - Housing/casing gas leaks/hot spots

A.2 Evaluation of HRSG/DB Configuration, Instrumentation, Controls, Operation Practices, Maintenance Practices, Unit Condition and Historical Data for Risk of DB-Induced Damage

The unit-specific equipment configuration, design and condition details; control effectiveness; historical operating data; actual exhaust gas and component temperature data; operation and maintenance personnel observations; and actual versus intended operating/maintenance practices must be compared with configurations, operating conditions and operating/maintenance practices understood to minimize pressure part damage from DB operation. Where insufficient data are available—such as actual exhaust gas and component metal temperatures—it may be necessary to develop specifications for additional instrumentation, data acquisition systems, and operational tests. Where key design limits are unavailable it may be necessary to utilize reverse engineering in conjunction with thermodynamic analysis of operating conditions over the range of DB operation experienced to establish useful limits for comparison to actual data. Evaluation, corrective action, additional data collection and reevaluation are often an iterative process over a time period of many months. Listed below are some steps in performing such an evaluation.

Step 1—Is the duct burner operated in strict accordance with design parameters? Plot and analyze trends in the following data, which may be obtained directly from or may be derived from the DCS historian:

- For the CT
  - Load
  - Inlet guide vane position/CT exhaust mass flow
  - CT exhaust gas mean temperature
- For the DB
  - Duct conditions at DB inlet
    - Temperature
    - Mass flow
    - Excess oxygen
    - Moisture content
    - Velocity
    - Distribution
  - Fuel
    - Side to side distribution
    - Top to bottom distribution
    - Manifold pressure
    - Heating value
    - Contamination
- For the HRSG
  - Steam conditions at outlet and inlet of primary and secondary HPSH and RH
    - Temperature
    - Pressure
    - Flow
    - Temperature ramp rate
    - Pressure ramp rate

- Metal temperatures
  - Superheater tubes
  - Superheater headers
  - Reheater tubes
  - Reheater headers
  - Evaporator tubes
- Evaporator
  - Tube heat flux
  - Tube internal deposits
- Attemperator
  - Spray flow rates
  - Amount of superheat at attemperator outlet
  - Stability of steam temperature control at attemperator outlet
  - Overshoot of steam temperature at SH/RH outlet
- Drum
  - Level control stability
  - Carryover limits
  - Cycle chemistry limits

Step 2—Determine the implications of not operating within design parameters, using available instrumentation plots in conjunction with a thorough thermodynamic analysis of stable and dynamic operating conditions over the range of DB operating conditions.

Step 3—Is existing damage evident? Outage inspection of:

- Flow distribution devices
- DB components
- Downstream HRSG components

Step 4—Determine root cause if damage is evident

- Characterize and document existing damage and patterns
  - Upstream exhaust flow devices
  - DB equipment
  - Burner duct
  - Down stream pressure parts

- Evaluate HRSG/DB configuration
- Evaluate existing instrumentation and controls
- Evaluate relevant operating practices
- Evaluate relevant maintenance practices
- Determine if additional instrumentation is necessary
  - Exhaust gas thermocouple arrays
  - Tube metal temperature arrays
- Conduct operational testing

Step 5—Determine and implement corrective action

Step 6—Is the result acceptable?

Step 7—Is future damage anticipated?

- Evaluate HRSG/DB configuration
- Evaluate existing instrumentation and controls
- Evaluate relevant operating practices
- Evaluate relevant maintenance practices
- Determine if additional instrumentation is necessary
  - Exhaust gas thermocouple arrays
  - Tube metal temperature arrays
- Determine if design modifications are necessary
- Conduct operational testing

Step 8—Determine and implement corrective action

Step 9—Is the result acceptable?

Step 10—Ongoing surveillance

- Annual inspection
- On-line condition monitoring system

B
DEMONSTRATION OF PRESSURE PART DAMAGE

Pressure part damage can result directly from off-design operation of duct burners as in Case Study 1. It can also result indirectly from the presence of a large duct burner as in Case Study 2. Many units designed for heavy duct burner firing operate at higher pressures than their unfired counterparts, resulting in much thicker pressure parts. These thicker pressure parts are subject to much greater damage than thinner pressure parts during severe thermal transients.

B.1 Case Study 1—Duct Burner Over-firing at 60% CT Load

This HRSG behind a GE-7FA combustion turbine suffered extensive damage to the DB, firing duct lining, HRSG casing and HP superheater tubes downstream of the DB. The DB was heavily fired with the CT at 60% load. The GE-7FA produces its hottest exhaust gas (≈ 1200 °F; 649 °C) near this load (Figures B-1 to B-4).

Figure B-1
Damage to Duct Burner Assembly and Firing Duct Stainless Steel Liner above Duct Burner. Overheating damage (not shown in photo) also occurred in the HRSG outer casing adjacent to locations where liner damage was most severe.

Figure B-2
Close Up of Duct Burner Damage

Figure B-3
Visible Evidence (Oxide Spalling) on First Row of Superheater Tubes (Unfinned) Downstream of Duct Burner

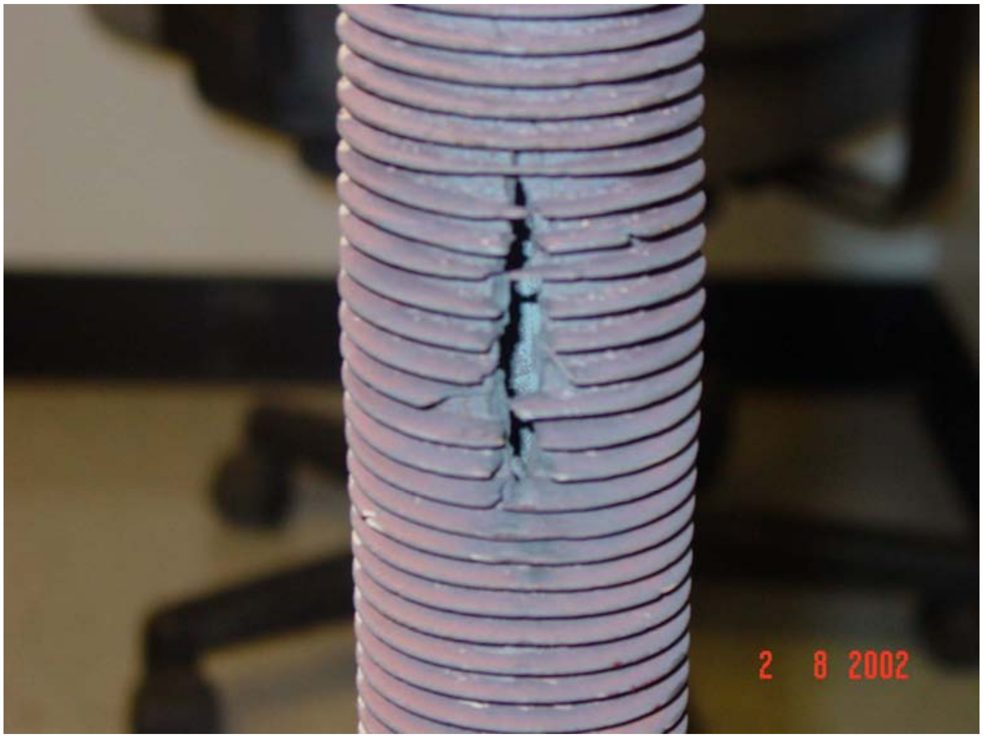

Figure B-4
Creep Rupture Failure in the Second Row of Superheater Tubes (Finned) Downstream of Duct Burner. It is one of many that occurred within three years of the over-fire event.

B.2 Case Study 2—HP Evaporator Under-Deposit Corrosion Damage Caused by Poor Duct Burner Fuel Distribution

A duct-fired HRSG in cogeneration service suffered severe under-deposit hydrogen damage to the leading row HP evaporator tubing. A wide range of NDE and metallurgical evaluations were performed to assess the deposition and corrosion patterns and to identify the type of under-deposit corrosion. In addition, detailed reviews of the historical and current operating practices and unit configuration were conducted. These reviews included:

- Unit design
  - Cycle chemistry limits
  - Return condensate system capabilities
  - HP evaporator circuit design
  - Design basis circulation
  - CT and DB influenced heat absorption rate considerations

- Construction
  - Preoperational storage history
  - Preoperational chemical cleaning
- Operation
  - Cycle chemistry upsets and out of limits operation
    - Frequency
    - Severity
    - Cumulative hours
  - Hours of off-design DB operation
  - DB trip/alarm history
  - HPSH trip/alarm history
  - HP evaporator trip/alarm history
- DB and HPSH and HP evaporator instrumentation maintenance/calibration/ history
  - Temperatures
  - Pressures
  - Flows
  - On-line cycle chemistry monitors
- Management directives in place with regard to steam and power production versus equipment damage avoidance

As might be expected in a cogeneration plant, condensate return concerns played a large role during the root cause analysis. However, while opportunities for improvements in condensate management were readily identified, there was an additional concern that excessive heat flux, especially during operation with duct burner in-service may also have influenced the waterside deposition and under-deposit corrosion damage. The initial investigation revealed that insufficient instrumentation existed to determine if the HP evaporator heat absorption rates and margins against local steam blanketing (departure from nucleate boiling, DNB) were being influenced by the wide range of CT/DB operating conditions experienced by the HRSG. Hence, it was not initially possible to eliminate DB operation as a factor in the excessive deposition rates and under-deposit corrosion.

The duct burners in this triple-pressure HRSG were located downstream of the final, 4-pass HP superheater harps and about 15 feet (4.6 m) upstream of the two-pass, 2nd HP superheater and 4-pass 1st HP superheater harps. The leading row of the HP evaporator was just downstream of the final row of the 1st HP superheater.

The 625-MMBtu/hr maximum output DB array consisted of seven burner runners with 207 orifices per runner. Engineering calculations revealed that under normal DB firing conditions, the burner openings (orifices) across the length of each burner runner should produce an average estimated flow of 17.9 lb/hr per orifice with a significant systematic variation of +20/-24% lb/hr (Figure B-5). This suggested that some significant gas temperatures and heat flux variations in the downstream tube coils could be present.

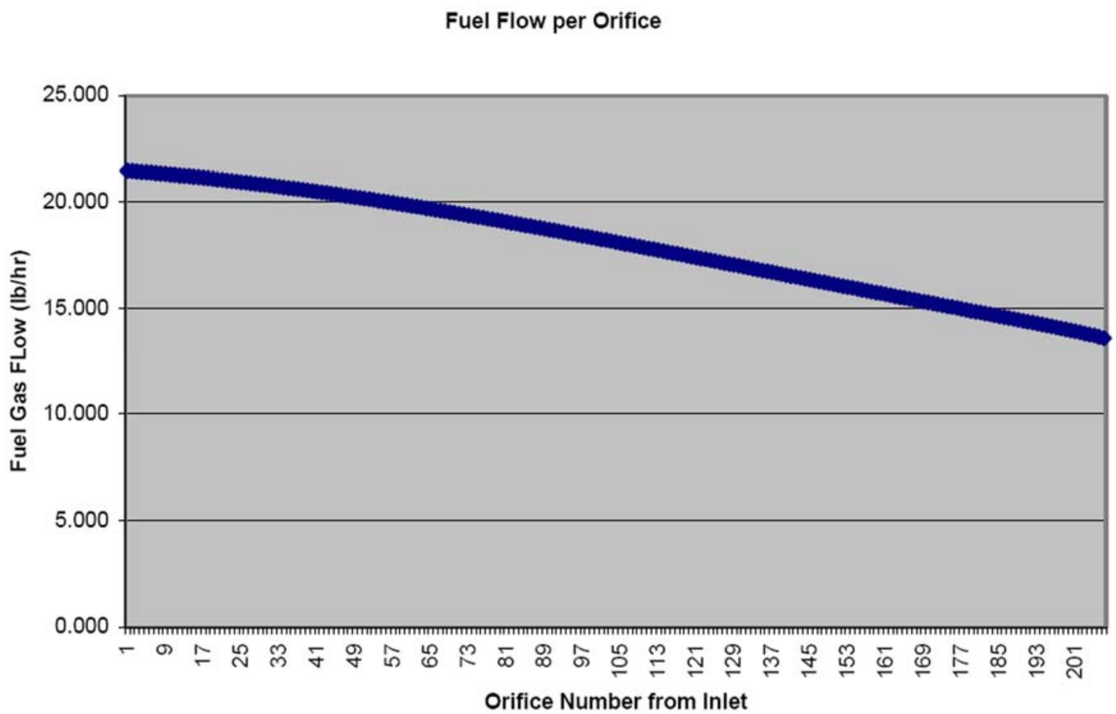

Figure B-5
Estimated Gas Flow across the Length of Duct Burner Runners. Due to the pressure drop in the runner fuel pipe the fuel flow rate is higher in the burner openings nearest the fuel inlet side of the runner.

To assess the influence of DB firing and the possible need for DB orifice tuning, measurements of the temperature of each of the outlet steam nozzle pipes in the HP Superheater 1 coil just downstream from the burner array was used to ensure design integrity and temperature uniformity associated with DB firing. The initial measured HP superheater 1 outlet nozzle temperature variations were as high as 34 °C (62 °F). In order to improve this side-to-side temperature distribution in the HP Superheater 1 coils, some of the burner orifices were plugged with a pin. More holes were plugged toward the gas inlet end of the runners. Some burner holes in the opposite end of the burner runners were enlarged.

To assess the influence of DB firing on the HP evaporator tubes and the possible need for further DB orifice tuning, a few dozen exhaust gas temperature and HP evaporator tube mid-wall thermocouples were installed across the face and in the leading row of the HP evaporator. These enabled the measurement of harp-to-harp, side-to-side, and top-to-bottom tube-metal and gas temperatures. Tube mid-wall thermocouples were installed in nine evenly spaced tubes across the front row of the HP evaporator coils. There were two thermocouples attached to each of the nine tubes, which were attached to the mid-wall-thickness of the leading edge of the tubing at a location 20% and 80% of the vertical height of the finned tubing. An array of gas-side thermocouples (attached to each of the four vibration supports) also was installed at the leading edge of the HP evaporator.

Findings from the gas-side thermocouples revealed that with the DB out of service and the combustion turbine operating at 67% or 100% of its normal full load value, there was a very uniform side-to-side and top-to-bottom gas temperature distribution (Figures B-6 and B-7). However with the DB operating at their preferred fuel flow rates for the part- and full-load CT operating conditions, there was still a significant (~ 50 °F to 70 °F) side-to-side and even more severe (~ 80 °F to 90 °F) top-to-bottom gas-temperature profile at the leading edge of the HP evaporator (Figures B-8 and B-9). This indicated that the initial modification of the burner orifices was not sufficient. This was further verified with HP Superheater 1 coil outlet steam nozzle pipe temperature measurements.

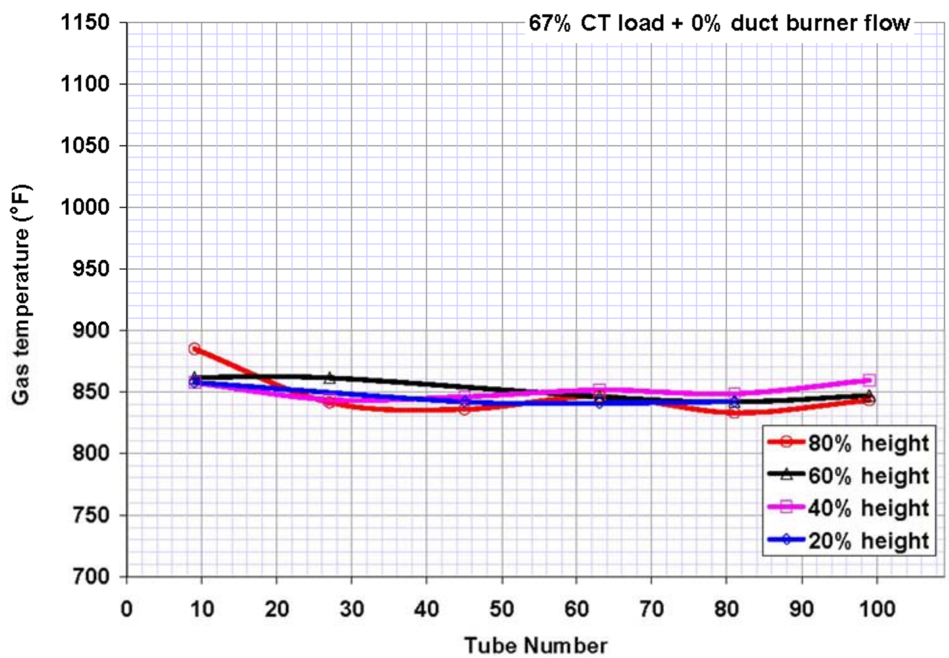

Figure B-6
Gas Temperatures at the Leading Row of the HP Evaporator with the Combustion Turbine at Approximately 67% of its Normal Operating Load and the Duct Burners Off

Figure B-7
Gas Temperatures at the Leading Row of the HP Evaporator with the Combustion Turbine at Approximately 100% of its Normal Operating Load with the Duct Burners Off

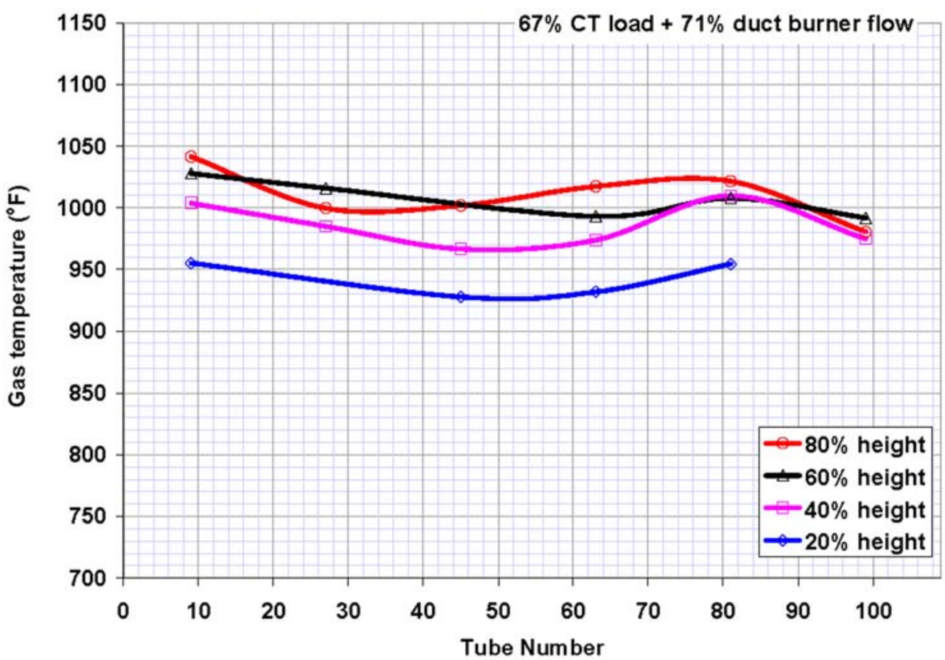

Figure B-8
Gas Temperatures at the Leading Row of the HP Evaporator with the Combustion Turbine at Approximately 67% of its Normal Operating Load and the Duct Burners Firing at Approximately 70% of their Normal Full Load Fuel Flow Rate

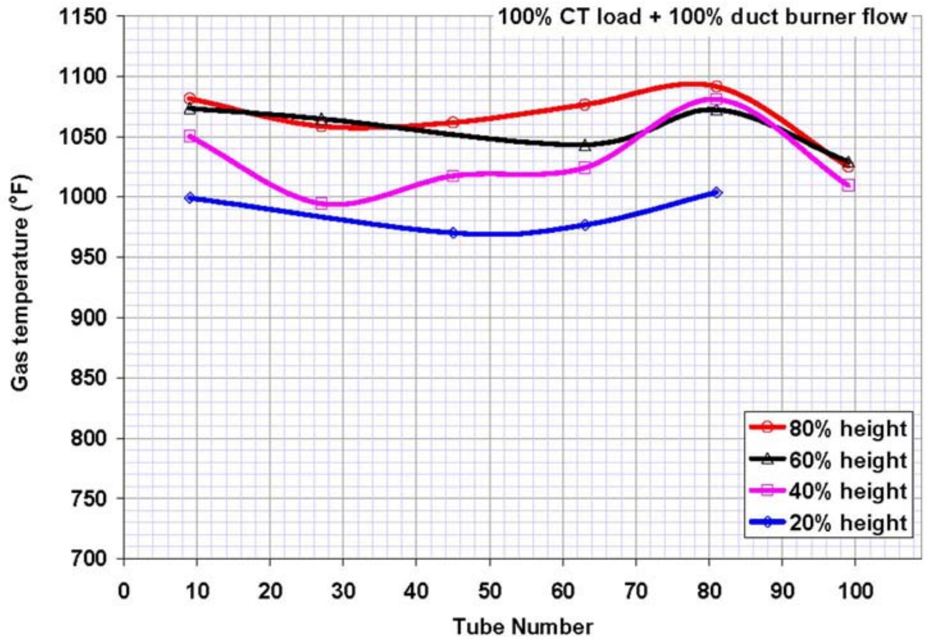

Figure B-9
Gas Temperatures at the Leading Row of the HP Evaporator with the Combustion Turbine at Approximately 100% of its Normal Operating Load and the Duct Burners Riring at Approximately 100% of their Normal Fuel Full Load Flow Rate

Prior to further tuning the DB, the measured HP evaporator mid-wall tube metal temperatures were evaluated and found to be moderate (Figures B-10 through B-13). With no duct firing, the maximum temperature pickup between the lower and upper measurement locations was 10 °F to 13 °F for 67% and 100% of the normal CT load, respectively. The maximum side-to-side tube-temperature variation was in the range of 8 °F to 11 °F with no duct firing. With the CT at 67% of its normal full load value and the DBs operating with 71% of their normal full load value, the maximum tube temperature pickup between the lower and upper measurement locations was 20 °F and the maximum side-to-side temperature variation was approximately 14 °F. With the CT at its normal full load value and the DBs operating at their normal full load value, the maximum tube temperature pickup between the lower and upper measurement locations was 28 °F and the maximum side-to-side temperature variation was approximately 20 °F.

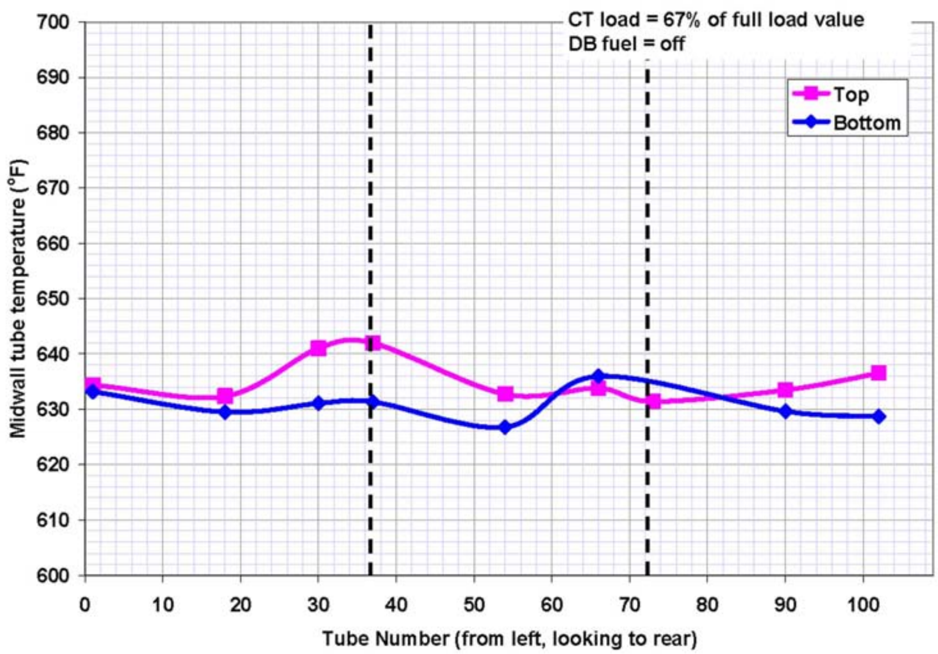

Figure B-10
Mid-wall Tube-metal Temperatures at the Leading Row of the HP Evaporator with the Combustion Turbine at Approximately 67% of its Normal Operating Load with the Duct Burners Off

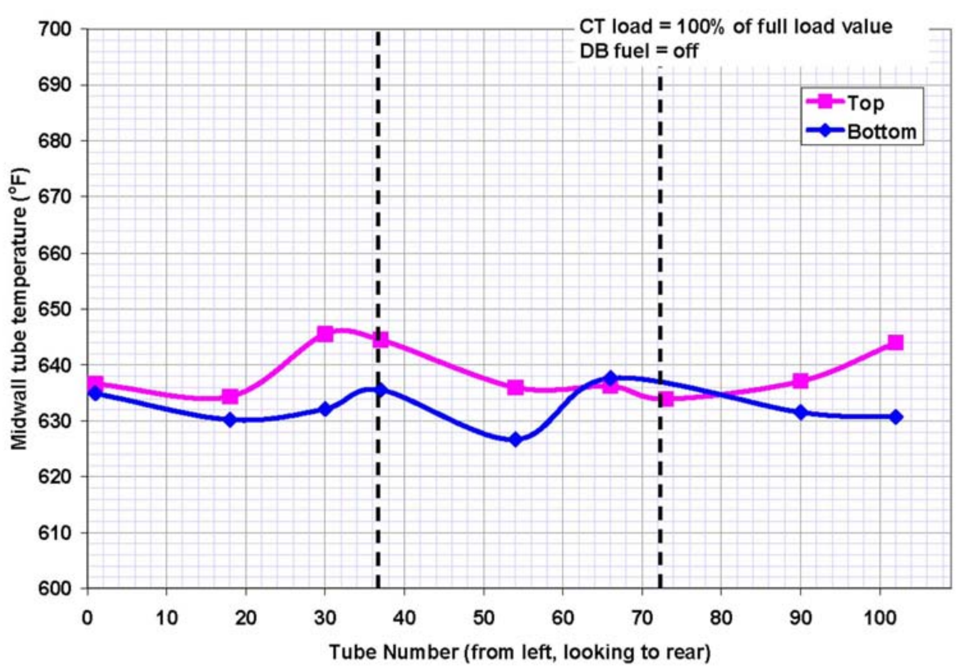

Figure B-11
Mid-wall Tube-metal Temperatures at the Leading Row of the HP Evaporator with the Combustion Turbine at Approximately 100% of its Normal Operating Load with the Duct Burners Off

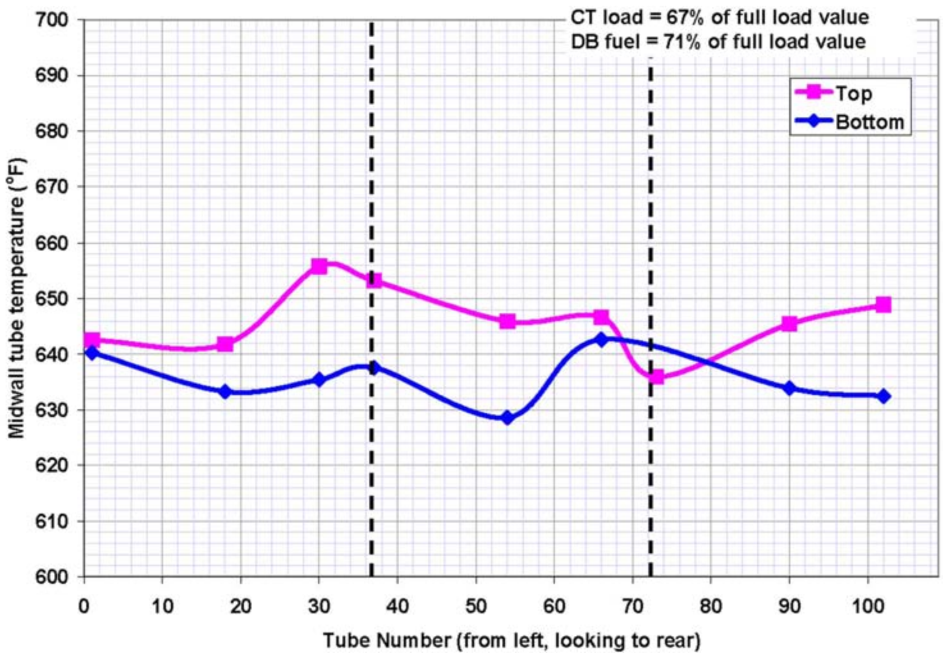

Figure B-12
Mid-wall Tube-metal Temperatures at the Leading Row of the HP Evaporator with the Combustion Turbine at Approximately 67% of its Normal Operating Load and the Duct Burners Firing at Approximately 71% of their Normal Fuel Full Load Flow Rate

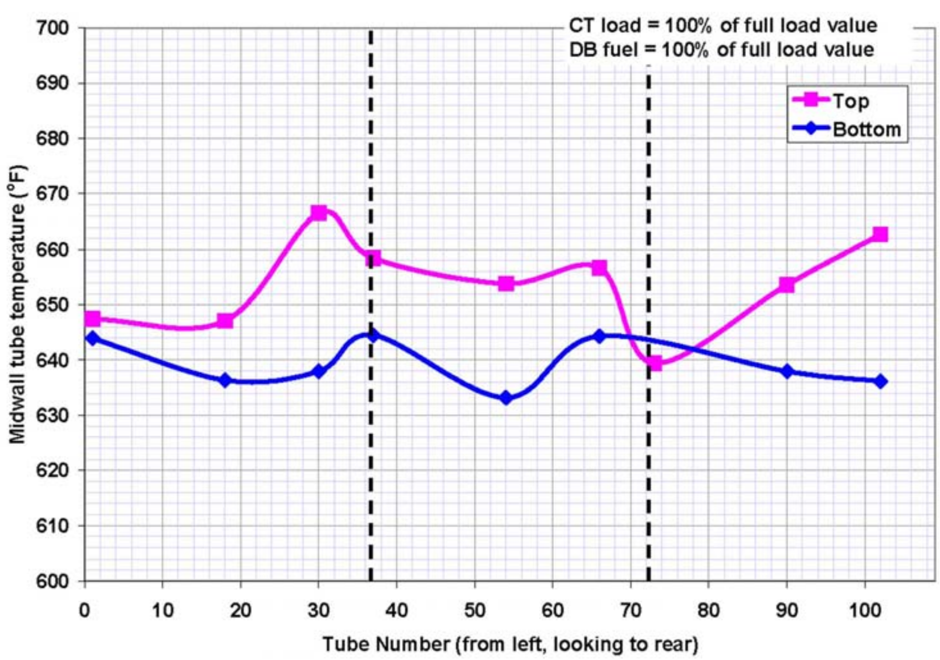

Figure B-13
Mid-wall Tube-metal Temperatures at the Leading Row of the HP Evaporator with the Combustion Turbine at Approximately 100% of its Normal Operating Load and the Duct Burners Firing at Approximately 100% of their Normal Fuel Full Load Flow Rate

Although the HP evaporator gas and tube metal temperature measurements and engineering calculations revealed that there was an adequate margin against departure from nucleate boiling, it was decided to make a second modification to the burner orifices. After this second modification, the HP Superheater 1 outlet header nozzle temperature variation during duct firing was decreased from 34 °C (62 °F) to 9 °C to 11 °C (16 °F-19 °F), which is deemed to be an acceptable variation.

Gas and tube metal temperatures were again measured during a wide range of CT and DB operating conditions. Detailed circulation, heat absorption, heat transfer, and margins against DNB evaluations were performed using new measured temperatures, pressures and flow rates. No evidence of DNB or near DNB conditions were found or analytically indicated to be possible after the DB modifications.

The mid-wall tube-metal thermocouples indicated a small (5 °F) side-to-side and moderate (19 °F) top-to-bottom mid-wall tube temperature in the leading row of the HP evaporator (Table B-1) under the worst case operating condition. Heat transfer estimates indicated that the measured tube metal temperatures were consistent with nucleate boiling heat transfer and that there was no evidence of departure from nucleate boiling (local steam blanketing). Detailed CFD modeling, calibrated with the measured gas and tube temperatures, revealed that even with the measured temperature elevated and mal-distributed temperatures associated with DB operation, there was still a large margin between the measured and design-basis critical heat flux required to avoid departure from nucleate boiling.

Table B-1
Measured Gas Temperature, Tube Mid-wall Temperature and Estimated Average Heat Flux Measured across the Leading Edge of the HP Evaporator at 20% and 80% Height Locations for 100% CT Load and Maximum Duct Burner Firing Conditions

80% height location	Left	Middle	Right
Tube mid-wall temperature	657 °F (347 °C)	655 °F (346 °C)	652 °F (344 °C)
Average Heat Flux	38,700 Btu/hr ft^2		
20% height location	Left	Middle	Right
Tube mid-wall temperature	641 °F (338 °C)	640 °F (337 °C)	638 °F (336 °C)
Average Heat Flux	30,600 Btu/hr ft^2		

Notes:
1. The left side (looking towards the rear of the unit) is the duct burner gas inlet side
2. Saturation temperature = 622 °F (327 °C)
3. CFD analysis indicates that the peak circumferential heat flux value in the leading row tubes was approximately 157% of the average heat flux values listed above
4. The estimated average and peak heat flux values for the 2nd row of the HP evaporator tubes were 23,600 Btu/hr ft^2 and 38,800 Btu/hr ft^2 (165% of average)

B.3 Conclusions and Recommendations:

The following conclusions and recommendations were made based on the diagnostic/troubleshooting monitoring and engineering evaluations discussed above:

- A DB heat maldistribution was found by measuring the gas temperatures at the leading row of the HP evaporator and the steam nozzle pipe temperatures in the HP superheater coil immediately downstream of the DB array.
- The initial DB temperature maldistribution was found to be excessive for the HP superheater coils
- Although not optimal, the temperature maldistribution was shown to have only a minor effect on the HP evaporator heat flux and margins against departure from nucleate boiling
- After two sets of burner tuning efforts, no unanticipated top-to-bottom or tube-to-tube gas or tube-metal temperature maldistributions were observed over a relatively wide range of steady-state and transient operating conditions
- Further monitoring of the tube-wall and gas temperatures is being performed for an even wider range of operating conditions—including conditions that produce steam production rates greater than 1-million lbm/hr.
- Changes to the cycle chemistry program included enhancements to the cycle chemistry monitoring instrumentation used, chemical additives used, improvements to the return condensate system, updated chemistry upset action limits, operating procedures and operator training
- Ongoing cycle chemistry, temperature monitoring, deposition and under-deposit corrosion surveillance has continued for a number of years.
- Although no further acute under-deposit corrosion has been detected, additional corrective actions are being considered to increase the tolerance of the HRSG and HP evaporator to periodic and sometimes severe upsets in condensate-return quality.

C
DAMAGE MONITORING SYSTEMS

C.1 Introduction

When designing complex equipment, such as the HRSG and DB system, the designer must make many assumptions about the operating conditions to which components will be exposed. For example, the design creep life of HRSG superheater tubes is significantly affected by the operating metal temperatures assumed by the designer in his pressure-part life calculations. If the actual operating temperature is just 10 °C (18 °F) higher than the assumed temperature, the tube will experience double the creep rate, hence it will last only half as long as anticipated. Similarly, the DB designer makes assumptions or relies on data given him by the CT and HRSG OEMs about exhaust gas characteristics at the inlet to the DB. These data are critical to the determination of DB flame length, flame temperatures, etc. If the actual DB-inlet conditions are different, flame impingement and overheating of downstream superheater tubes is a real possibility. Technical papers reporting the results of large scale measurement of actual HRSG tube metal temperatures demonstrate that it is quite common for a designer's assumptions and actual data to differ significantly.

The typical plant instrumentation is not designed to collect sufficient operating data internal to the HRSG to test the accuracy of many key design assumptions. Therefore, if a new HRSG is to be operated with confidence that the specified pressure part design life can reasonably be attained, the owner should specify and employ during commissioning a robust HRSG damage monitoring system. Such a system is comprised of temporary thermocouples mounted throughout the steam system—anywhere from 100 to 500 of them, depending on the make and model of HRSG—and rented data acquisition equipment. During the fabrication and erection of an HRSG at a new construction site, these temporary thermocouples are likely to be damaged. As a result, the damage monitoring system should be installed after most of the construction efforts are completed, and just before commissioning.

Once the system is installed, the plant should be run through all anticipated operating modes while data are collected. Such modes typically include steady-state CT load, steady-state DB firing rate, the full range of CT load ramp rates, the full range of DB firing ramp rates, the full range of startup and shutdown types, with and without CT inlet-air conditioning operating, with and without steam/water injection, etc. There is a practical limit to the time and effort that can be expended on this endeavor, before the temporary thermocouples begin failing in large numbers or the rental cost of the data acquisition system becomes too high. Once all of the data has been collected, it must then be carefully analyzed and key component absolute temperatures, differential temperatures, and temperature ramp rates must be compared to the design assumptions.

Some of the key locations for the temporary thermocouples are the top and bottom of the first row of superheater tubes downstream of the DB. Typically, it is not necessary to instrument each tube in the row, but a sufficient number of them should have thermocouples installed so that any significant side-to-side temperature differences are detected. Similarly, an array of exhaust gas thermocouples should be attached to the upstream DB support structure. These thermocouples must be shielded from DB flame radiation and a sufficient number of them must be installed to accurately profile localized exhaust gas temperature as it enters the DB.

If employing the damage monitoring system on a new unit for early detection of problems—and while the vendors are still commercially responsible—it may be sufficient to install only the superheater tube thermocouples. If no excessive deviations from design assumptions are noted and no visible problems with DB performance are noted, then the time and expense of documenting the actual exhaust gas temperature profile into the DB can be avoided. If however tube temperature data indicate that superheater tube life is being shortened by DB operation, or if DB-related superheater damage is evident, then the exhaust gas thermocouples should be installed at the same time as the tube metal thermocouples. If attemperator over-spray is suspected as a result of DB operation it may be necessary to also install some thermocouples on the final superheater upstream of the DB. Some of these thermocouples should be located on tubes near the steam inlet nozzles to the final superheater, while others should be located well away from these nozzles.

A damage monitoring system can be extremely useful not just during commissioning, but also throughout the service life of a combined cycle plant. Such a permanent damage monitoring system might consist of 50 to 100 thermocouples wired to the plant's DCS historian. It also would include DCS real-time plots and alarms of actual versus expected absolute temperatures, differential temperatures, and temperature ramp rates. The permanent system should provide a historical record of events when components are exposed to conditions outside of design limits, a count of such events per component, the degree to which the limit as exceeded, and the duration of each event. Some systems even attempt to provide automated analysis of remaining component life based on data from the damage-monitoring system. For a new construction project, the permanent damage monitoring system can be installed by the OEM during fabrication of the HRSG.

C.2 Temporary Damage Monitoring System Arrangement and Installation

The use of temporary thermocouples spot-welded directly to HRSG tubes, rental data acquisition equipment, and a stand-alone PC has proven to be an inexpensive means of collecting large quantities of damage-monitoring data. The spot-welded thermocouple has a very low thermal inertia, hence it can respond rapidly enough to capture short-term thermal events—such as a slug of condensate or colder steam passing through a tube. To ensure that the temporary damage monitoring system lasts the several weeks needed to gather a comprehensive set of data; installers must pay careful attention to the following details.

Thermocouples should be installed behind header gas baffles to shield them from aerodynamic excitation from the exhaust gas and to give access to the un-finned portion of tube near the header.

It is often necessary to make a penetration of the HRSG casing near the heating coil being instrumented to allow the temporary thermocouple leads to exit. A threaded pipe nipple welded to the outer casing and packed with insulation after the thermocouple leads are installed makes an inexpensive temporary penetration seal. After completion of testing and removal of thermocouple leads from the nipple, the penetration may be permanently secured by packing it with insulation and screwing on a threaded pipe cap.

A secure location shielded from exhaust gas leaks, hot pipes, steam jets, etc. should be identified for temporary installation of the data acquisition equipment. Fluke equipment capable of transitioning up to 25 thermocouples per unit to Ethernet cable can be rented. To minimize the length of thermocouple leads, you can locate some Fluke units at the top of the HRSG and others at the bottom. The Fluke units must be provided with a 110-VAC power supply and protected from the weather. Depending on site conditions and requirements, temporary enclosures have been fabricated from metal, plastic storage tubs. and plywood.

From start to finish it is critical that the labeling of thermocouple leads match exactly the actual thermocouple location in the HRSG, that external labels remain securely attached and legible, and that thermocouple leads are protected from physical damage.

Prior to conducting operational testing it is important to:

- Ensure that the sampling rate, scale factor, polarity, etc. for each thermocouple are accurately set.
- Confirm that the memory and data storage capacity of the PC used to collect the thermocouple data is sufficient to handle the large data files that may result.
- Establish how and when data will be extracted and/or backed up from the PC to avoid over-writing or otherwise lost data.
- Synchronize the time clocks of the PC and DCS system.

Some owners have utilized the plant's PI system for storage and plotting of temporary thermocouple data.

Thermocouple Attachment

The following procedure has been successfully used on carbon steel, T11, T22 and T91 tubes and headers.

Thermocouple Preparation

- Bare two ends of a type K thermocouple for a distance of about 0.5 inch (1.27 cm).
- Make a 90-degree bend half way on each wire in the same direction.
- Ensure opposite ends are not connected together (each wire isolated from the other).

Tube Preparation

- Sand all oxide/scale off the TC attachment spot on the tube (approximate 1 inch (2.54 cm) dia.)
- Do not attach thermocouple in a tube bend, or within 1 inch (2.54 cm) of a bend or a weld.

Preheat

- T91 - preheat local area to 300 °F (150 °C) (DO NOT use an oxy-acetylene flame on T91).
- CS, T11, T22 - preheat to 200 °F (93 °C).

Spot-welding

- Using a capacitor discharge machine, place the magnetic ground clamp within 3 inches (7.6 cm)of the TC attachment spot. (Pinch clamp may be use instead, for pinch clamps; ground may be further away on header or header attachment. When using a remote ground, over 2 feet (60 cm) away, increase the weld intensity to “high”, if needed).
- Set the discharge machine on automatic and medium weld intensity. (Manual may also be used).
- Grab one wire with the pliers welder (or hemostat long neck pliers) and touch to the tube.
- The machine will "fire" in about three seconds on auto, push red button to manual fire.
- Using a fine piece of emery cloth or stainless steel brush, remove any black firing residue from the area where the next wire will attach.
- Grab the second wire; note the machine is ready to fire (green light).
- Pick a spot about 0.125 inches (3 mm) from the first weld and no further than 0.25 inch (6.3 mm).
- Weld the second wire.
- Brush residue with a stainless-steel wire brush.

Post Weld Inspection

- Inspect for distance between thermocouple wires of less than 0.250 inches (6.3 mm).
- Inspect for sound welds visually and attempt to slightly wiggle TC attachment.
- Visually inspect for no cracks – use PT to resolve questions (ANSI II or III NDT required).

Corrective Action

- If any unsoundness or excessive distance between wires is noted, remove grind spots, shift location 0.5 inch (1.27 cm) and repeat steps.

Once the thermocouple is successfully welded to the tube, its leads must be carefully arranged, secured, tested and insulated. The following procedure should followed:

- Secure the thermocouple lead to the tube about 1.5 inches (3.8 cm) from the spot-welds using stainless steel tie wire. Leave a small amount of slack in the thermocouple lead between the wire tie and the spot-welds to prevent stress on the weld attachments.
- Spread the thermocouple wire between the outer sheath and the spot-weld so that the bare portions of thermocouple wire have no possibility of touching each other. Otherwise, the thermocouple will read gas temperature rather than tube metal temperature.
- Ring out each thermocouple by heating it with a low temperature torch or hot air gun while a helper monitors for a response at the far end of the lead with a portable thermocouple reader. Confirm that the tube location noted on the lead's external label tag agrees with the actual location of the thermocouple.
- Wrap the tube with high temperature fiberglass insulation for a distance of 1.5 inches (3.8 cm) above and below the spot-welds. Secure the insulation with a stainless steel tie wire top and bottom.
- Arrange thermocouple leads into neat bundles near the header as they proceed toward the HRSG casing exit point.
- Secure the individual thermocouple leads and/or bundles to tubes hear the header every 18 inches (46 cm).
- Wrap bundles and/or individual thermocouple leads with protective high temperature fabric to prevent chafing or physical damage where necessary.
- Be ware that exhaust gas flow during operation can reach 35 mph and will cause fatigue failure of any unsecured thermocouple leads.
- Take care not to damage thermocouple leads when replacing header gas baffles.

C.3 Permanent Damage Monitoring System Arrangement and Installation

While well installed spot-welded thermocouples can last for many months, they are not suitable for a permanent damage monitoring system. Permanent systems require the use of thermocouples with relatively low thermal inertia for fast response, but a more durable attachment method than the direct spot-welding employed with the temporary system. Thermocouple leads in permanent systems are typically run thorough conduits attached to headers or tubes. This avoids damage during maintenance activities. Welded tab thermocouples provide a secure, longterm attachment, but may be too slow to detect very rapid temperature transients if large tabs are employed. Thermocouples embedded in flame sprayed aluminum have been used in some installations, and appear to give good response and good reliability.

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