Influences of HRSG and CCGT Design and Operation on the Durability of Two-Shifted HRSGs

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Abstract
The durability of HRSGs in two-shifted cyclic service is significantly influenced by a few key HRSG design, combustion turbine control, balance-of-plant design and combined cycle unit operation choices. This paper seeks to identify the most significant of these choices and quantify their relative importance in reducing thermally induced fatigue damage to superheater and reheater components. The paper also describes how significant reductions in fatigue damage can be achieved in existing plants by altering combustion turbine control characteristics and combined cycle unit operating procedures.

Introduction
The superheaters, reheaters, evaporators, economizers and preheaters in all HRSGs develop peak thermally-induced stresses in headers and in tube/pipe connections to headers during every combustion turbine/HRSG startup and shutdown. The magnitude of the peak tensile and compressive stresses induced by the transiently high thermal gradients is strongly influenced by arrangement and detailed design of the HRSG tubes, headers and interconnecting pipe work. It is also strongly influenced by the design of combustion turbine (CT) combustion controls, by the design of some plant auxiliary systems, and by the operating procedures utilized during unit startups and shutdowns. The influence of HRSG design choices and unit operating procedures on cyclic stresses and fatigue damage expenditure rates during startup-shutdown cycles have been highlighted in previous papers [1, 2]. They are more extensively discussed in the EPRI documents referenced in the paper entitled " HRSG Dependability" presented at this same conference[3].

The durability of critical parts of the HP superheater (SH) and reheater (RH) during cycling (two-shift) operation is strongly influenced by their design and the CT exhaust gas characteristics produced during startups and shutdowns. The higher temperature sections of SH and RH experience the most severe changes in gas and steam temperatures during CT/HRSG startups and shutdowns. They also operate on load at high temperature when creep relaxation of the residual strains resulting from local yielding at locations of peak inelastic stresses, (so-called creep fatigue interaction), considerably accelerates the rate of accumulation of plasticity at very localized high stress points. Creep fatigue interaction substantially increases the cyclic life expended during each startup-shutdown cycle.

This paper provides a quantitative perspective of the influence of different design choices for HRSG, CT combustion system controls and of alternative operating procedures during startups and shutdown on the cyclic life of SH and RH tubes at their attachment welds to the headers. Actual metal temperatures, measured via thermocouples attached to tubes near their tube-to-header connection, and to headers, are presented to demonstrate and quantify the thermal transients discussed.

Damage Mechanisms in HP SH and RH

HP, SHs and RHs are susceptible to 3, possibly 4, damage mechanisms; thermal-mechanical fatigue, creep fatigue, thermal quenching induced fracture, and possibly corrosion fatigue at tube attachments at lower headers of the higher temperature sections where condensate collects simultaneously with the occurrence of transiently high tensile stresses during pre-start purges and shutdowns

SHs and RHs in all designs of large HRSG are susceptible to creep - fatigue damage during startups and shutdowns at three locations:

- The toe of the weld on the tube attaching it to the header
- The intersection of tube-holes with the bore of some headers
- Pipe branches on outlet manifolds

Two mechanisms develop thermal stresses at the toe of tube-to-header welds of SHs and RHs.

- Transient temperature differences between tube and header during:
  - rapid heating of tubes during startup by rapid increase in CT exhaust gas temperature
  - chilling by un-drained condensate blown forward when steam flow is established during startups
  - condensation quenching of tubes and lower headers during CT shutdown, spin-cools and purges
- Transient or steady-state thermally-induced bending forces in individual tubes

This paper is focused primarily on just one of the foregoing mechanisms: the potential thermal fatigue damage caused by transient temperature differences between tubes and headers during unit starts and shutdowns.

The other mechanisms summarized above are no less important to understand and quantify: some have the potential to be even more damaging. They have been discussed and demonstrated qualitatively in previous papers[1, 2, 3], and reports[4, 5]. Some quantitative perspective on the risk of cracking from the intersection of tube holes and header bores is included in another paper at this conference[3], and more extensively in other reports[5].

Thermal Fatigue in SH and RH caused during starts and shutdowns by transient temperature differences between tubes and headers

Large tube-to-header temperature differences occur during CT/HRSG starts, in the tubes exposed most directly to the hot inlet gas, developing transiently high compressive thermal stresses at the toe of the tube-to-header (Figure 1). The diameter of the tube transiently outgrows the hole to which it is attached.

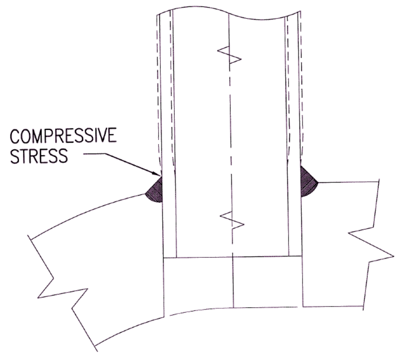

Figure 1 - Thermal Stresses Caused by Transient Tube-to-Header Temperature Difference During CT/HRSG Startups

The transient tube-to header temperature differences occur because the finned, thin-walled tubes directly exposed to the hot gas follow much more closely the large, rapid rise in CT exhaust gas temperature than the comparatively thicker headers, which are shielded from the gas flow (Figure 2). During the initial stage of the startup there is little or no steam flow through the tubes and headers of SH or RH, and thus little heat input to the inner surfaces of their headers.

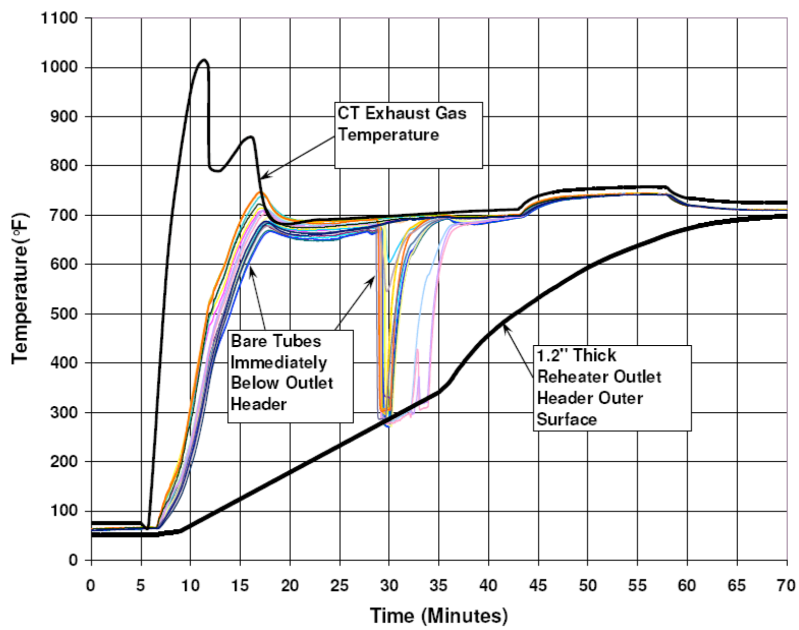

Figure 2 - Reheater Outlet Tube and Header Temperatures During Cold Startup (CT: 7FA DLN 2.6 with Exhaust Gas Temperature Matching)

Prior to synchronizing, there is little or no scope for modifying the CT exhaust gas characteristic because the CT must be accelerated to synchronous speed through several critical speed bands as quickly as possible. However, once the CT has been synchronized it can be held at minimum CT generator output with minimum stable exhaust gas temperature for as long as necessary to match, as closely as possible, the requirements of

HRSG and steam turbine. The minimum exhaust gas temperature, obtained with the CT operated with a very small nominal generator output, varies for the different CT models and also for the particular CT model, depending upon the type of combustion system and combustion controls installed.

Influence of SH and RH header thickness and diameter on thermal fatigue at tube attachments to headers

During the initial heating process at startup, the rate of increase in header bulk wall temperature is strongly influenced by header thickness (Figure 3). Minimization of header thickness significantly reduces the peak transient temperature difference between tubes and headers, and thus also the peak thermal stresses in the tubes at the toe of the attachment weld. Minimization of header diameter is doubly beneficial. In addition to allowing proportional reduction in header thickness, circumferential temperature gradients are also reduced since heat conduction from the tubes is significant in the initial header heating process.

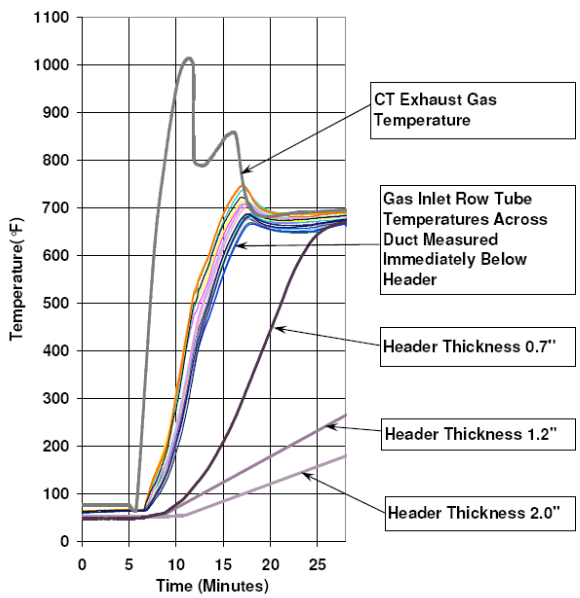

Figure 3 – Tube and header outer surface temperatures measured on SH and RH headers of different thickness during cold startup (CT: 7FA DLN 2.6 With Exhaust Gas Temperature Matching)

Peak tube-to-header bulk wall temperature differences based on measured metal temperatures during cold starts are provided in Table 1 for headers of different thickness. An estimate has been provided of the cycles to crack initiation for each case and is included in Table 1 to provide a perspective of the influence of header thickness on the rate of thermal fatigue damage accumulation during cold starts.

The cyclic life estimates provided in Tables 1, 2, 3, 4 & 5 should not be interpreted as precise because there are significant uncertainties, some conservative and others non-conservative, in both the calculation method and the determination of life expenditure per cycle. The cyclic life estimates in Tables 1 through 5 are intended to highlight the considerable impact of alternative design choices and methods of operation on cyclic life of tubes of higher temperature sections of SH and RH at their attachment welds to headers.

Although there is uncertainty as to whether, and to what extent, the cyclic life estimates in Table 1 (also Tables 2 through 5) may be conservative or non-conservative, any error in life estimate is likely to be reasonably consistent for the three header wall thicknesses tabulated so that the proportional improvements in cyclic life for thinner headers are likely to still apply.

Table 1
Thermal Fatigue Life Estimates at Gas-inlet Row Tube-to-Header
at Toe of Weld on Tube to Outlet Header

Header Thickness mm (inch)	Tube-to-Bulk* Header Wall Temperature Difference °C (°F)	"Benchmark"** Estimate of Cold Start Cycles to Initiate Tube Wall Crack
50.8 (2.0)	311 (560)	850
30.5 (1.2)	297 (535)	970
17.8 (0.7)	222 (400)	2300

* - Bulk header wall temperature estimated from measured outer surface temperature

** - "Benchmark" estimates of thermal stress and cycles to crack initiation in Table 1, (and generally also Tables 2 to 5, inclusive), are based on the following assumptions:
- No hoop stress, only a bending stress in the tube wall
- Excludes creep-fatigue interaction, which is non-conservative, possibly very non-conservative for SH and RH sections that operate at higher temperatures
- Assumes that no negative tube-to-header temperature differences and tensile stresses occur during the cooling part of the thermal cycle at shutdown, which is non-conservative, possibly considerably so
- Assumes $K_t = 1.0$ at toe of weld to tube, which is non-conservative
- Neglects heat conduction from tubes to header and the resulting localized temperature gradients within the header wall, which is conservative, possibly significantly so
- Applicable in horizontal gas path type HRSGs only to those designs which have a single row of straight tubes per upper and lower header pair

Influence of tube and header arrangements in SH and RH on cyclic life

The data in Table 1, and also Tables 2 to 5, is applicable only to large vertical gas path HRSGs and to those designs of horizontal gas path HRSGs that utilize panels each having a single row of straight tubes connected without any bends to an upper and lower header such that any thermal-mechanical axial forces that may occur in individual tubes causes no bending moment, but only direct reactions at their attachments to the headers at each end.

During startups, when the CT exhaust temperature is increasing rapidly, there is a significant reduction in the gas temperature across each successive row of tubes as heat is transferred from the gas to the finned tubes. Therefore, transiently the temperature of each successive row of tubes lags behind that of the preceding row in gas flow direction by an amount which diminishes progressively from the gas inlet row (Figure 4). Similar findings from temperature measurements on other designs of HRSG have been reported previously [2, 3, 5].

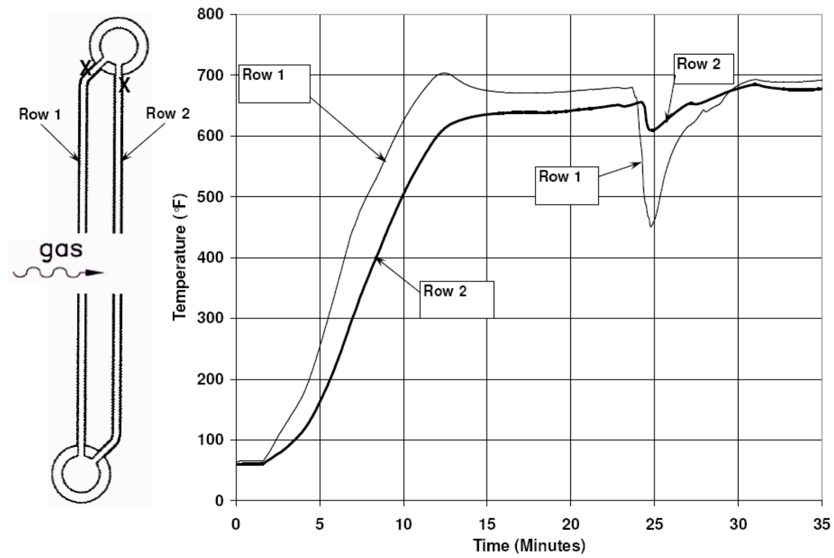

Figure 4 - Two-Row Parallel Pass Tubes/Headers Panel ΔT Between Average Tube Outlet Temperatures of Gas Inlet and Second Row Tubes

When SH and RH panels utilize a single row of tubes per upper and lower header pair, a transient temperature difference between successive tube rows doesn't develop any tube forces or moments at the tube attachment weld to the headers-- provided the interconnecting steam pipes between successive headers has adequate flexibility to accommodate the transient temperature difference between tube rows. However, in horizontal gas path HRSGs with SH or RH panels with two or more parallel pass rows of tubes that share the same upper and lower headers (Figure 5), then the tubes in each row develop significant thermal-mechanical axial forces during starts when the tube rows are transiently heated to different temperatures. Adjacent tube row temperature differences as high as 80°C (144°F), during initial startup, have been recorded in several designs of HRSG.

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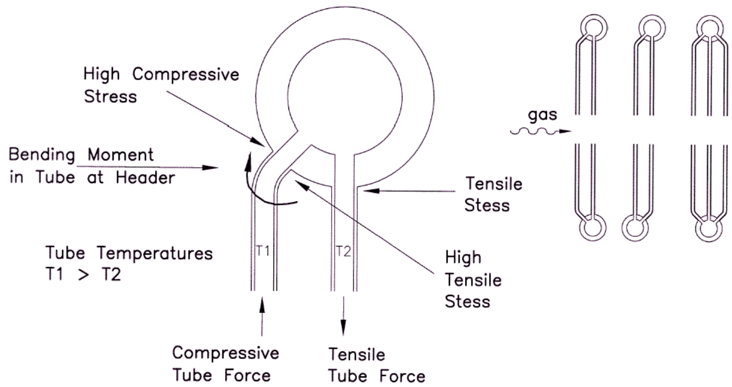


Figure 5 - Parallel Pass Tube/Header Panels Intensify Thermal Stress at Bend Attachments to Headers

Furthermore, when more than a single row of tubes share the same upper and lower headers, then inevitably one or more of these tube rows are connected to the headers by tube bends. In consequence, the axial forces in the tubes develop a bending moment as well as a direct force which causes a localized high compressive stress at the toe of weld attaching the tube to the header. The occurrence of this transient high compressive bending stress developed by thermal-mechanical tube forces coincides with the period during the CT startup when the peak temperature difference between tube and bulk header wall also develops a high compressive bending stress at the same location. This substantially increases the peak transient thermal stress and considerably reduces the cyclic life predictions compared with those for tube panels with a single row of tubes assumed for cyclic life estimation in Table 1.

For even limited two-shift cycling operation, it is recommended that horizontal gas path HRSGs utilize panels with a single row of straight tubes per pair of upper and lower headers with flexible interconnecting pipes in SH and RH sections.

Influence of CT exhaust gas temperature at minimum CT output on thermal fatigue in SH and RH tubes

The stable exhaust gas temperature available from the CT when held during CT/HRSG startups at nominal minimum CT generator output for the initial HRSG heat soak significantly influences fatigue life of tubes at attachment welds to SH and RH headers.

The minimum CT exhaust gas temperature provided by “F” and equivalent class or larger CTs when at minimum CT generator output varies significantly (Figure 6). Furthermore, some CTs have quite different CT exhaust gas temperature characteristics when operated at lower outputs depending on which alternative combustion system and which combustion control system is installed. For example, the basic GE frame 7FA with DLN2.6 combustion system is installed without “exhaust temperature matching” (ETM). ETM is an optional modification to the combustion control system intended to enable lower steam temperatures to be produced during cold starts to match the maximum steam temperature limits for initial heat soaking of the steam turbine. ETM should be installed on all frame FA CTs. Without it the significantly higher CT exhaust gas temperature produced at minimum CT output develops very damaging transient thermal stresses in tubes and headers of SH and RH during startups and even more so during shutdowns. (discussed later)

The influence on peak SH and RH tube-to-header temperature differences of the minimum stable CT exhaust temperature obtainable from the CT when operated at minimum CT generator output is illustrated for cold starts in Figure 6. Table 2 provides a "benchmark" estimate of the corresponding cyclic life of tubes at the toe of the weld to header for headers of different thickness. These cyclic life estimates assume that there is no negative tube-to-header temperature difference during the cooling part of the thermal cycle, which is unrealistic. The estimates are intended to highlight the significant reduction in cyclic life expenditure rates at tube to header attachment welds provided by those CTs which produce lower exhaust gas temperature when held at minimum CT generator output. Even for frame FA CTs on units intended for a lifetime of continuous operation the benchmark cyclic life predictions in Table 2 indicate that combustion controls must be installed with ETM, particularly where the HRSG has SH headers thicker than about 25mm (1 inch).

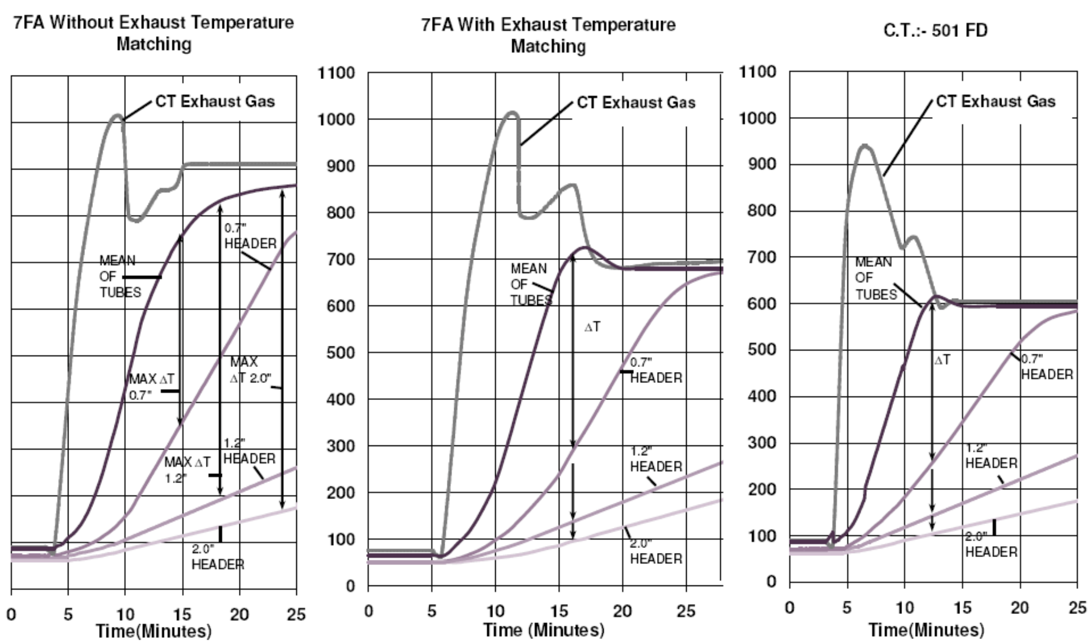


Figure 6 - Influence of CT Exhaust Gas Temperature at Minimum CT Load on Tube-to-Header ΔT During Cold Startup for Headers of Different Thickness

Table 2
Thermal Fatigue Life Estimates at Gas-inlet Row Tube-to-Header
at Toe of Weld on Tube to Outlet Header

Header Thickness mm (inch)	CT: GE-7FA without "Exhaust Temp Matching" Exh.Gas 488°C(910°F) @ min. CT output		CT: GE-7FA with "Exhaust Temp Matching"Exh.Gas 378°C (710°F) @ min. CT output		CT: SWPC-501Fl Exh.Gas 321°C (610° min. CT output	
	Tube-to-Header Bulk Wall _T. °C (°F)	"Benchmark" estimate of cold start cycles to crack initiation	Tube-to-Header Bulk Wall _T. °C (°F)	"Benchmark" estimate of cold start cycles to crack initiation	Tube-to-Header Bulk Wall _T. °C (°F)	"Benc estin colc cyc cr init:
50.8 (2.0)	350 (630)	600	311 (560)	850	247 (445)	1,
30.5 (1.2)	325 (585)	740	297 (535)	970	236 (425)	1,
17.8 (0.7)	225 (405)	2,240	222 (400)	2,300	175 (315)	4,

Note: - All caveats listed after Table 1 apply also to Table 2

Influence of HP saturation temperature prior to startup on thermal fatigue at tube attachment to outlet header of SH and RH

During the shutdown period, the headers in the HP section of the HRSG remain reasonably close to the prevailing HP saturation temperature as it falls during the offload period. Thus the saturation temperature in the HP section of the HRSG just prior to commencing the CT startup significantly influences the SH and RH tube-to-header temperature differences (Figure 7).

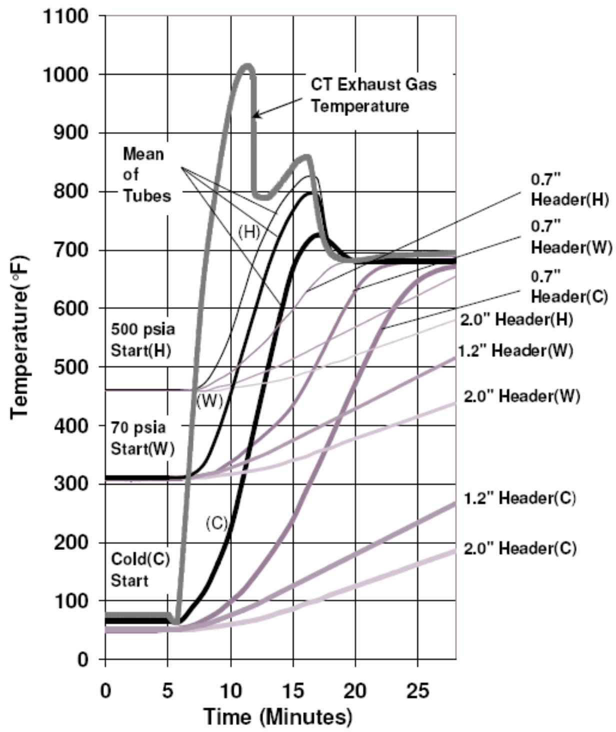


Figure 7 - Influence of Initial Temperature Before CT Startup on SH/RH Outlet Headers (7FA with Exhaust Temperature Matching)

The "Benchmark" estimates of cyclic life of tubes at attachment welds to their headers highlight substantial reductions in life expenditure per startup are achieved by maximizing the HP pressure and saturation temperature prior to the startup. The estimates in Table 3 err towards non-conservatism because, as also is the case for the life predictions in Tables 1 & 2, the life estimates in Table 3 have unrealistically assumed there is no negative tube-to-header temperature difference during the cooling part of the thermal cycle that occurs at CT/HRSG shutdown. Nevertheless, the cyclic life estimates in Table 3 illustrate the crucial importance of using shutdown procedures that maintain high HP pressure in the HRSG after shutdown and then minimize pressure decay during the offload period for units expected to perform some two-shift operation.

The cyclic life estimates in Tables 4 & 5 do account for both heating and cooling parts of the cycle.

Table 3
Thermal Fatigue Life Estimates at Gas-inlet Row Tube-to-Header
at Toe of Weld on Tube to Outlet Header

Header Thickness mm (inch)	Cold start from ambient temperature. [CT exh gas 377°C (710°F) at min output]		Warm start from 4.83 bara (70psia). [CT exh gas 377°C (710°F) at min output]		Hot start from 34.5 b (500psia). [CT exh gas 377°C (71 min output]	
	Tube-to-Header Bulk Wall _T. °C (°F)	"Benchmark" estimate of cold start cycles to crack initiation	Tube-to-Header Bulk Wall _T. °C (°F)	"Benchmark" estimate of warm start cycles to crack initiation	Tube-to-Header Bulk Wall _T. °C (°F)	"Benc estin hot cyc cr init
50.8 (2.0)	311 (560)	850	211 (380)	2,700	142 (255)	8,
30.5 (1.2)	297 (535)	970	200 (360)	3,200	128 (230)	12
17.8 (0.7)	222 (400)	2,300	172 (310)	5,000	100 (180)	25

Note: - All caveats listed after Table 1 apply also to Table 3.

Importance of correct design and operation of SH and RH drains

In Figure 2, the sudden fall in temperature at about 27 minutes into the startup of the upper outlet of some of the RH tubes was caused by condensate which could not be removed because of design deficiencies in the drains system. The undrainable condensate was blown forward and chilled some of the tubes to saturation temperature while many of the tubes attached to the same upper and lower headers remained about 222°C (400°F) hotter. The chilled tubes developed large tensile forces which were significantly intensified by the bending moment in this RH panel, which has two rows of parallel pass tubes attached to the same upper and lower headers. Condensate chilling of some tubes is an additional source of severe fatigue damage at the same tube to header welds that also experience fatigue damage caused by peak tube-to-header temperature differences earlier in each CT/HRSG startup.

The large tube temperature anomalies caused during startups by condensate chilling of selective tubes has been highlighted in other reports together with recommendations for corrective action pertaining to drain system design in order to eliminate this very damaging phenomenon [1, 2, 3, 4, 5].

Minimizing the risk of cracking from the intersection of tube holes and header bore

Although this paper has focused mostly on the thermal fatigue at tube-to-header welds, startups and shutdowns also induce transiently high compressive and tensile stresses at the intersection of tube holes with the header bore that can be even more damaging than those caused by tube-to-header temperature differences.

The factors that strongly influence the severity of peak thermal stresses developed at the intersection of tube holes and header bore are similar to those that influence the peak thermal stresses at tube-to-header welds during startup and shutdown; namely minimize SH and RH header thickness and diameter, minimize CT exhaust gas temperature at minimum output, maintain HP pressure as high as possible prior to each restart, heat soak the HRSH at minimum CT output, and control CT exhaust gas temperature ramp rates to the more restrictive of the limits set by HRSG or steam turbine.

These issues are discussed and quantified in more detail in other reports. [(1, 3, 5)]

Influence of combined cycle unit startup procedure on cyclic life of SH headers

Key features recommended for CT/HRSG startups (Figure 8) include:

- The initial HRSG heat soak should always be performed with minimum CT exhaust gas temperature to minimize the peak tube-to-header temperature difference and also the thermal stress developed at the intersection of tube holes and header bores

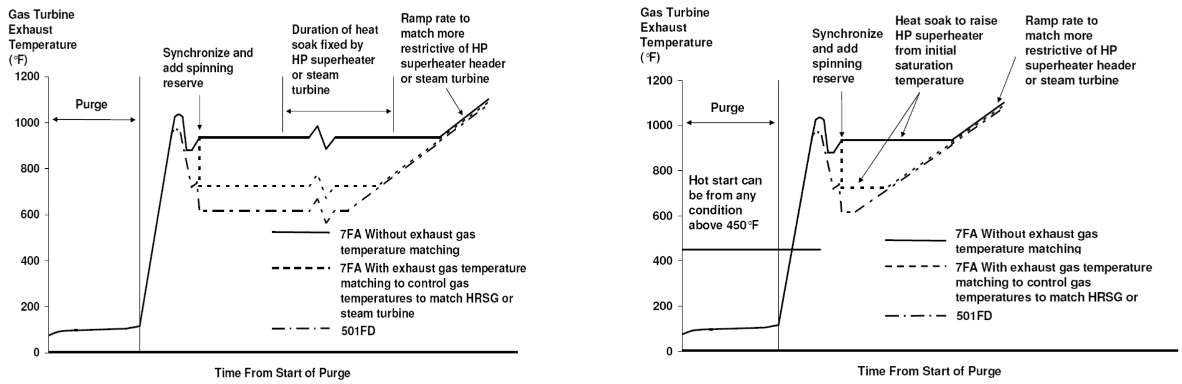
- Determine hold durations and ramp rates from the initial HP saturation temperature before startup considering the thickness and diameter of the critical SH header and the HP saturation temperature prior to startup

- Select the limiting HP steam temperature ramp rate for the more restrictive of SH header or steam turbine

- Control CT exhaust temperature holds and ramps by providing an adjustable set point from the DCS to the CT control system

- Using the HP SH and RH interstage attemperators during ST startup to obtain appropriate HP steam to steam turbine metal temperature matching can result in significant damage to the HRSG. Overspray into saturation and the subsequent chilling of selected tubes poses a significant risk of large tube-to-tube temperature differences

- Using a second HP SH attemperator installed after the final SH outlet to lower HP steam temperature to match steam turbine limits provides no mitigation of the significant thermal stresses experienced by SH and RH tubes and headers with CTs that have excessively high minimum exhaust gas temperature. It also increases the risk of severe steam turbine damage during manual operation when controls inevitably malfunction.



(Cold Startup) *(Hot Startup)*

Figure 8 - Gas Turbine Exhaust Temperature Characteristics at Startup

Influence of combined cycle unit shutdown procedure on cyclic life of SH headers

Many CTs cannot maintain emission limits for NOx production below 50 to 60% CT output. The widely used practice of rapid deloading and shutdown of the CT from this CT output (Figure 9) may be very damaging to the SH lower headers at both the welds attaching the tubes to the header and also at the intersection of the tube holes with the header bore.

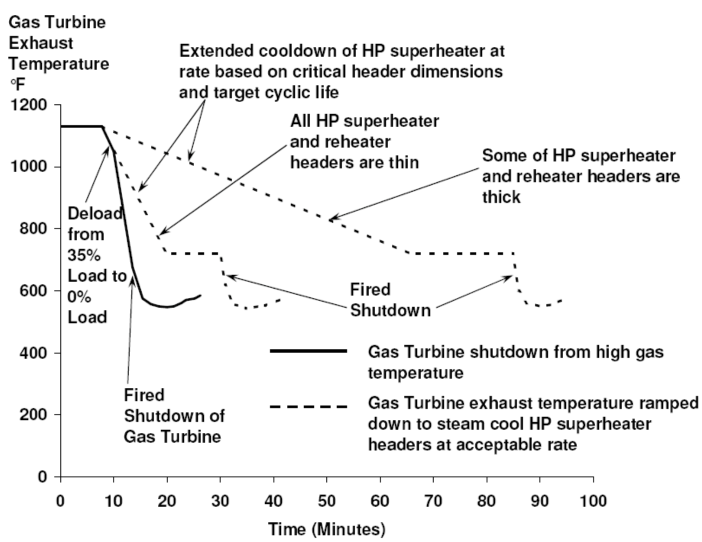


Figure 9 – Alternative Methods of CT/HRSG Shutdown
(7FA DLN2.6 With & Without Exhaust Gas Temperature Control)

During CT deloading prior to shutdown, the tubes of SH and RH closely follow the reducing CT exhaust gas temperature, whereas the headers cool at a slower rate strongly influenced by the header thickness. This develops a negative tube-to-header temperature difference and tensile thermal stress at the toe of the weld attaching tube to header

(Figure 10). The peak transient tensile thermal stress occurs during final deloading or deceleration of the CT when gas temperature falls below saturation temperature in the SH causing condensation in the finned tubes which runs down and quenches the tubes and tube holes in the lower headers.

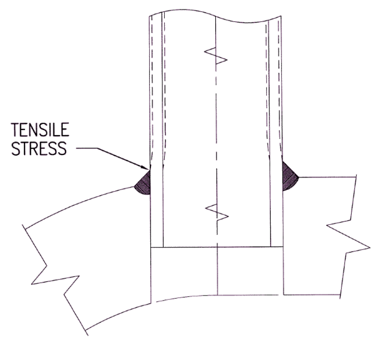


Figure 10 – Thermal Stresses Caused by Transient Negative Tube-to-Header Difference During Steam Cooling or Condensate Chill at Shutdown

To prevent severe chilling by condensate of the SH tubes and lower header inner surfaces the shutdown must be extended so that CT exhaust gas temperature can be lowered at a linear rate dictated by the thickness of the thickest SH or RH header. This "steam cooling" of the headers at the appropriate rate limits the tensile thermal stresses at tube-to-header attachments on lower headers and also at the intersection of tube holes and header inner surface. Tables 4 and 5 highlight the substantial reductions in thermal fatigue damage rates at tube-to-header attachment welds achieved by an extended shutdown procedure. An example of the benefits of extended shutdowns to cyclic life of headers at the intersection of tube holes and bore is provided in Table 3 of Reference 3 and in more detail in other reports[5].

Table 4
Thermal Fatigue Life Estimates at Gas-inlet Row Tube-to-Header
at Toe of Weld on Tube to Outlet Header

Header thickness mm (inch)	Peak tube-to- header bulk wall _T [CT exh. gas temperature at min load 377°C (710°F)]					*"Benchmark" estimate of cold start-shutdown cycles to initiate tube wall crack	
	_T during cold start	Using quick CT shutdown		Using extended CT shutdown to steam cool SH headers			
		_T during shut-down	Total _T range per cold start-shutdown cycle	_T during shut-down	Total _T range per cold start-shutdown cycle	Using quick CT shutdown	Using extended CT shutdown
50.8 (2.0)	311 (560)	-189 (-340)	500 (900)	-56 (-100)	367 (660)	200	520
30.5 (1.2)	297 (535)	-189 (-340)	486 (875)	-56 (-100)	353 (635)	220	580
17.8 (0.7)	222 (400)	-189 (-340)	411 (740)	-56 (-100)	278 (500)	370	1,190

* Note: - All caveats listed after Table 1 also apply to Table 4, except that the tube-to-header temperature difference range accounts for both heating and cooling effects. Data in Table 5 assumes CT exhaust gas temperature of 377°C (710°F) at minimum output.

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Conclusion

The benchmark estimates of the cyclic life provided in Table 5 provide a perspective of the significant influence that SH and RH header thickness and operating procedures used during CT/HRSG startups and shutdowns have on the cyclic life of SH and RH tubes at their welds to headers.

Table 5 highlights the importance of limiting header thickness to about 25 mm (1 inch), using the extended shutdown procedure to steam cool SH and RH headers and maximizing HP pressure upon shutdown.

For horizontal gas path HRSGs, the cyclic life estimates are valid for panels having only a single row of straight tubes per upper and lower header pair. Horizontal gas path HRSGs constructed with panels having more than one row of tubes attached to the same headers will have significantly lower cyclic lives and are not recommended for units intended for two-shifting.

Table 5
Thermal Fatigue Life Estimates at Gas-inlet Row Tube-to-Header
at Toe of Weld on Tube to Outlet Header

Header thickness mm (inch)	Method of Shutdown	Total tube-to-header _T range per startup-shutdown cycle °C (°F)			* "Benchmark" estimate of cycles to initiate tube wall crack		
		Cold start & shutdown	Warm start & shutdown	Hot start & shutdown	Cold start & shutdown	Warm start & shutdown	Hot start & shutdown
50.8 (2.0)	Quick	500 (900)	400 (720)	331 (595)	200	400	710
	Extended	367 (660)	267 (480)	197 (355)	520	1,350	3,330
30.5 (1.2)	Quick	486 (875)	389 (700)	317 (570)	220	430	810
	Extended	353 (635)	256 (460)	183 (330)	580	1,530	4,170
17.8 (0.7)	Quick	411 (740)	361 (650)	289 (520)	370	540	1,060
	Extended	278 (500)	228 (410)	156 (280)	1,190	2,160	6,780

* Note: - All caveats listed after Table 1 also apply to Table 5, except that the tube-to-header temperature difference range accounts for both heating and cooling effects. Data in Table 5 assumes CT exhaust gas temperature of 377°C (710°F) at minimum output.

Recommendations

- HRSG design issues
  - Limit the thickness and diameter of all HP SH and RH headers to minimize tube-to-header temperature differences and tolerate faster gas and SH/RH outlet steam temperature ramp rates
  - Use panels with a single tube row per upper and lower header pair to eliminate additional bending stresses at offset tube – to – header welds
  - Ensure that SH and RH drain systems quickly and reliably drain all condensate from tubes, lower headers, pipes and manifolds. The "worst case" for sizing drain pipes and valves is generally at atmospheric pressure
- CT design influences
  - Ensure that the CT exhaust gas temperature peak on startup occurs and then the gas temperature is reduced again within about 5 minutes. This will prevent even larger transient tube to header temperature differences.

- Minimize the CT exhaust gas temperature at minimum spinning reserve load. This minimizes the SH and RH header tube-to-header temperature differences during startup and shutdown.

- Ramp CT exhaust temperature to protect HRSG critical headers as well as the steam turbine. Specify CT controls to do so.

• Balance of Plant influences
  - Specify HP / Hot Reheat bypasses capable of high volumetric flow during startup. Bypasses sized for full CT load and full pressure cannot pass sufficient steam at low pressures to heat soak critical HRSG pressure parts at sufficiently low saturation temperatures during startup

  - Open the HP Bypass early (at CT startup on warm and hot starts) to provide cooling steam in the SH / RH to avoid high tube-to-header temperature differences

  - A reliable source of auxiliary steam is essential to seal glands and raise vacuum prior to CT start for early bypass use

• Operations Influences
  - Ensure SH and RH drains are correctly operated to remove all condensate within 1 or 2 minutes of CT ignition

  - Ensure HP bypass is opened as early as possible after CT start to cool SH and RH tubes and begin the heating of headers, pipes and manifolds

  - During startups, use selected an exhaust temperature hold and ramp rate that will protect the limiting component; SH header or steam turbine

  - During shutdowns, lower CT exhaust temperature only at the fastest rate acceptable to the thickest SH header

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