Quantifying Thermal Transients in Heat Recovery Steam Generators

Presented at: EPRI: International Conference on Boiler Tube and HRSG Tube
Failures and Inspections; November 2-5, 2004 in San Diego, California.

Authors: Robert W. Anderson, Progress Energy
Michael Pearson, J. Michael Pearson & Associates

1 Introduction

Many papers and reports have been published by the authors of this paper and by others during the past several years to draw attention to some undesirable features commonly used by Heat Recovery Steam Generator (HRSG) and balance of plant designers for HRSG pressure parts and critical auxiliaries, respectively. This includes certain aspects of widely used operating practices for combined cycle unit starts and shutdowns that are particularly damaging to the HRSG. Although some progress has been made to address some of the concerns previously raised, there remains skepticism by some who choose to take the position that the concerns have been overstated.

The more recent papers and reports referenced in this paper included quantitative data to support the previously expressed concerns. This paper provides further evidence, selected from extensive tube temperature measurements made on the final reheater of an “F-class” HRSG, of the severity of the temperature differences and associated thermal-mechanical forces and stresses that transiently occur during combustion turbine (CT)/HRSG starts and shutdowns, and also during certain on-load operating conditions.

2 Reheater 2 Arrangement

The final reheater (RH2) is located at the inlet of the HRSG heat transfer section and exposed directly to the exhaust gas from a 7FA CT, Figure 1. In direction of gas flow, the final heating section of the high pressure superheater (HPSH) is immediately behind RH2, followed then by the primary reheater section (RH1).

RH2 comprises two rows of parallel-pass tubes, both rows connected to the same lower inlet and upper outlet headers; Figure 2 is the view from the gas inlet side of RH2 looking towards the HRSG stack. The gas inlet, or front, row 1 tubes are straight tubes connected at 12:00 and 6:00 o'clock, respectively, to the bottom inlet and top outlet headers. The rear, row 2 tubes, which are arranged directly in line with those of the preceding front row tubes in the direction of gas flow, each incorporate a bend at each tube end to connect the tube to the same top and bottom headers.

The headers and tubes of RH2 are top supported by fixed supports attached to the upper headers. Thermal expansion of the tubes when heated during operation is accommodated by downward expansion of the RH2 tubes and lower headers in conjunction with some distortion of the tubes to accommodate differences in thermal expansion between row 1 and row 2 tubes that occurs throughout both stable and unstable operation.

Row 1 and row 2 each have 66 tubes divided equally between the two bundles. Each of the two lower headers has two inlet pipe branches opposite tubes #9 and # 25 in the left hand bundle and tubes #42 and #58 in the right hand bundle. The two upper outlet headers also each have two outlet pipe branches positioned opposite the same tubes as the lower header pipe branches.

Steam is transferred from four pipes, two on each RH1 bottom outlet header, through a horizontal "U" shaped manifold to which are connected the four inlet pipes, two connected to each of the two lower inlet headers of RH2, Figure 3. The reheater (RH) desuperheater spraywater injection nozzle is located immediately downstream of and less than 1 pipe diameter from the outlet of the second 90° small radius bend of the "U" manifold pipe. The first branch to RH2 inlet on the manifold is located only about 7 pipe diameters downstream of the desuperheater nozzle.

The U manifold has three drain connections, one at each of the two blind ends and the third in the short straight spool between the two 90° bends. The manifold was installed horizontally, without any slope, when cold. While in this condition it has no fall towards the drain connections, such that condensate will pool along the bottom of the long length of manifold between the drains. When tubes are hot, and during transient heating of the tubes at startup, the RH2 tubes expand downwards further than those of RH1, and so any condensate that collects in the bottom of the manifold connected to the RH1 outlet pipes will tend to flow towards the RH2 section of the U manifold.

RH and HPSH drains are all connected to the same blowdown vessel. Although the blowdown tank is in a pit intended to provide gravity drainage of condensate, in practice there is inadequate static head to quickly drive RH drains into the blowdown tank when there is no pressure in the RH. Furthermore when HPSH and RH drains are both in operation, as they should be throughout the prestart purge, the large drain flow from the HPSH may raise the pressure in the blowdown vessel above that in the RH, in which case there is a risk of reverse flow in the RH drains and of blowing slugs of condensate from the blowdown vessel into the RH manifold, lower headers and selectively through some tubes to the top outlet headers.

3.0 Potential Cyclic Life Problems for RH2

The arrangement of tubes, headers and interconnecting pipes and RH desuperheater in the subject HRSG incorporates several design features that have been highlighted in previous papers and reports by the authors and others as sources of potentially high thermal-mechanical stresses induced by significant temperature differences between the individual tubes of RH2. (References 1, 2, 3, 4, 5 and 6).

The material damage mechanism of principle concern in RH2 is creep fatigue. Tube temperature differences that transiently develop localized inelastic strains at the toe of tube-to-header attachment welds expend a proportion of the fatigue life of the material during each thermal cycle, Where the material experiences significant creep at the high temperature dwell part of the thermal cycle (on-load operation), as is the case in RH2, then later during on-load operation creep relaxation of the residual stresses resulting from localized plastic deformation during the high strain parts of the thermal cycle (startup and shutdown) substantially increases, possibly by a factor as high as 10, the life expended by each thermal cycle.

To obtain reliable data on RH2 tube and header temperature transients during startups, shutdowns and on-load operation of the CT and HRSG, approximately 100 tube thermocouples (TC) were spot welded to the unfinned area of selected tubes near the tube-to-header welds of RH2, Figure 4. TCs were installed at the top and bottom of a proportion of both front and rear row tubes. TCs were also installed on the outside surface of the outlet header. Care was taken to avoid spot welding on tube bends or directly adjacent to welds. The TCs were located behind gas baffles where gas convection effects are small. Where access permitted tube and TC were also wrapped with insulation to eliminate the possibility of any gas temperature influence and ensure that the TCs accurately recorded the tube metal temperatures.

3.1 The influence of pressure parts design choices on the severity of transient thermal mechanical stresses at tube attachment welds to headers.

During stable operation under most operating conditions, all tubes in HPSH and RH of many designs of HRSG usually operate with closely similar mean tube temperatures and with tube ends at similar temperature to the header to which they are attached. Under the foregoing conditions, thermal mechanical stresses in tubes and headers are innocuous.

However, TCs installed on many tubes of HPSH and RH of several different designs of HRSG have highlighted that very significant transient temperature differences between tubes, also between tubes and headers, often occur during CT starts, shutdowns and in some instances during on-load operation.

Three mechanisms, each of which develop significant restrained thermal gradients and damaging thermal stresses, have been highlighted by the TCs installed on the tubes and headers of the subject RH2:

- (i) Transiently high row 1 to row 2 tube temperature differences during every CT start that develop thermal-mechanical axial forces in all tubes because both rows of tubes are attached to the same top and bottom headers; (refer to sections 3.2.1 and 3.2.2, below).
- (ii) Transiently high tube to header temperature differences during every CT start and shutdown; (refer to section 3.3, below).
- (iii) Selective chilling, in some cases severe quenching, of a proportion of the tubes by condensate of different origins; (refer to section 3.4, below).

All three mechanisms develop peak thermal stresses at the same position on the tube outer surface at the toe of the tube-to-header attachment welds and thus their damaging effects are additive. The first two mechanisms occur simultaneously and thus increase the cyclic stress range, which may substantially increases the life expenditure per cycle.

The magnitude of the transient peak temperature differences that develop thermal stresses by mechanisms (i) and (ii) can be predicted with more certainty from TC data than can the temperature differences developed via mechanism (iii). Tube and header temperature transients, and the associated thermal stresses, caused by mechanisms (i) and (ii) are strongly related to the HRSG arrangement of RH and HPSH sections, by the thickness of headers, by the CT exhaust gas temperature characteristic during acceleration and operation of the CT at minimum CT load, by the HP drum pressure prior to the start, and by the operating procedure utilized during the initial part of the CT/HRSG start. The third mechanism, tube-to-tube temperature differences caused by chilling via condensate migration, is the most difficult to detect. This is due to its being unit specific because it is strongly influenced by the design and arrangement of RH and HPSH drains, attemperators, operating and maintenance practices, etc, and can only be quantified on any particular HRSG installation by attaching TCs to many judiciously selected tubes.

Previous papers have discussed more fully the first two mechanisms and provided more extensive data from the subject RH2 and from the HPSH and RH of other designs of HRSG, References 1, 2, 3, 4, 5, and 6. In order to emphasize the importance of addressing all potential sources of cyclic damage to RH2 of concern with the subject RH2, the first two mechanisms have also been included in this paper together with a portion of the more extensive quantitative temperature data provided in References 3 and 6.

However, it is the new data published in this paper related to condensate migration that is of greatest concern because it highlights that selective, transiently random, chilling or quenching of a proportion of tubes in a bundle can develop very severe temperature differences between adjacent tubes, which cannot be detected or quantified, unless many TCs are attached to many of the RH and HPSH tubes. Therefore, it is crucially important to identify all of the potential sources of condensate in RH and HPSH of all designs of HRSG and eliminate these sources from new designs and implement modifications on installed units that mitigate the more damaging sources.

3.2.1 Panels with parallel-pass tube rows and shared headers are susceptible to high thermal-mechanical stresses

Whenever row 1 tubes operate with a higher temperature than the row 2 tubes, then the larger thermal expansion of the row 1 tubes is resisted by the lesser expansion of row 2 tubes, resulting in compressive thermal mechanical forces in the hotter row 1 tubes and tensile forces in the somewhat cooler row 2 tubes, Figure 5. Likewise, when the presence of condensate fleetingly and selectively chills one or more tubes below the temperature of the majority of the other tubes in both tube rows, the transiently chilled tubes experience large tensile forces.

When two or more rows of tubes are attached to the same upper and lower headers, it is inevitable that one or more tubes are offset from the vertical centerline of one or both headers and connected to the header by a bend, Figure 5. The bending moment at the weld attaching each offset tube to the header, caused by thermally induced forces in the tubes whenever the entire tube row or individually chilled tubes operate at different temperatures, substantially increases the peak thermally induced stress above that which results from the direct thermally-induced force applied by a straight tube to the header. It has been suggested by others that the headers may rotate in response to temperature differences between rows, thereby reducing stresses at the weld. While this may, to a limited extent, be true in some cases where only small bore drains are attached to the lower header, it is not so in this case due to the substantial rigidity of the RH1 to RH2 interconnecting piping restraining rotation of the lower headers.

3.2.2 Rows 1 to row 2 tube temperature differences during startups

RH2 has two tube rows attached to the same upper and lower headers. Row 1 tubes are straight and the row 2 tubes have a bend at each end to connect the tubes to the headers, Figure 2. When operating at baseload, the average temperature of row 1 tubes is of the order of 10°F higher than that of row 2 tubes. This difference in average temperature between row 1 and row 2 tubes increases to of the order of 20 to 25°F when operating the CT at part loads between 85 to 125MW, which is probably too small to be a fatigue concern, even conservatively assuming a stress intensification factor of 4 or 5 from the bending moment in the offset row 2 tubes. However, significantly larger temperature differences develop between row 1 and row 2 tubes at every CT startup during acceleration of the CT to speed and initial loading.

Figure 6 plots the individual tube temperatures of RH2 row 1 and row 2 tubes measured just below the outlet header during a startup on 1-12-03 using CT Exhaust Gas Temperature Matching (ETM), which limits the CT exhaust gas temperature when operating at minimum CT load to a little over 700°F. The tubes develop a large spread in temperature during the final stages of acceleration to speed and synchronizing of the CT generator. Prior to about 28 minutes on the time axis of Figures 6, there was no steam flow through the RH. Thus the finned row 1 tubes closely followed the rapid increase in CT exhaust gas temperature during acceleration of the CT to speed and after initial loading of the CT. Some of the heat in the CT exhaust gas is removed in the row 1 tubes, thereby lowering the gas temperature into row 2 tubes and thus also of the row 2 tubes, which therefore lag behind the row 1 tubes during the initial phase of the CT/HRSG startup.

Figure 7 utilizes the same tube temperature versus. time data as Figure 6, but has averaged the row 1 and row 2 tube outlet temperatures. The maximum difference in average temperature of row 1 and row 2 tubes reaches about 150°F, which is a significant concern for the offset row 2 tubes. Furthermore, the peak thermal stresses developed in the row 2 tubes at their attachment welds to the headers, by the row 1 to row 2 tube temperature difference of about 150°F, is significantly increased by an additional transient thermal stress developed simultaneously by high tube-to-header temperature differences during every CT startup; (refer to section 3.3, below).

3.3 Tube-to-header temperature differences at tube attachment welds during startups

During every startup, the finned RH2 tubes shadow the rapid rise in CT exhaust gas temperature much more closely than the thicker headers to which they are attached, causing the tubes to expand thermally in diameter relative to the hole in the header to which they are welded, Figure 8. The initial rate of tube temperature rise is similar at every startup because cooling steam flow through the RH cannot be established until after the HP bypass has opened later in the start and the CT produces a similar exhaust gas temperature versus time characteristic during the acceleration phase to synchronous speed at each startup, at least up to the point where the generator is synchronized. However the rate of heating of the headers, and thus the peak difference in temperature between tubes and header wall in proximity to the tubeholes, is strongly influenced by the thickness of the headers, which are heated predominantly by condensation on their inner surfaces and by conduction from the comparatively thin tubes.

Figure 9 plots the tube temperature data measured at the outlet of RH2 tubes during the 1-12-03 startup, together with the outer surface temperature measured on headers of different thickness in the hottest sections of the HPSH and RH. The thicknesses of HPSH and RH2 outlet headers are 2.0" and 1.2", respectively, while the lower return header of HPSH is about 0.7" thick.

Figure 9 illustrates the substantial influence of header thickness on the magnitude of peak tube-to-header temperature difference during startups. Further measured data quantifying the influence of header thickness on tube to header temperature differences during startups from various initial conditions, for different CT exhaust gas characteristics and also during shutdowns using different procedures are provided in References 3 and 6.

During each start, the sharp change in temperature between tube and header develops a compressive bending stress and hoop stress at the tube surface at the toe of the attachment weld to the header that on row 2 tubes is additive to the peak transient thermally-induced compressive bending stress developed by the row 1 to row 2 average tube temperature difference discussed in sections 3.2.1 and 3.2.2, above. Sophisticated analytical modeling supported by data from cordal thermocouples judiciously placed in a header close to tubeholes, both beyond the scope of this paper, would be required to quantify the peak compressive stress developed on the surface of the row 2 tubes by these two thermally induced loading mechanisms that occur simultaneously at every startup. Without the results of such work, the prudent action recommended for horizontal gas path HRSGs intended for even limited cycling service is to exclude the possibility of damaging thermal stresses caused by tube row to row temperature differences by precluding the use of multiple rows of tubes that share the same top and bottom headers. Likewise, limiting the maximum thickness of higher temperature headers to about 1 inch reduces the tube to header temperature difference and associated thermal stress substantially such that extensive cycling should not be a concern.

Since it is the cycle stress range that determines cyclic life, the prediction of cycles to crack initiation requires determination also of the magnitude of the peak thermally-induced tensile stress at the same location on the row 2 tube attachment welds, which occurs during the shutdown part of each thermal cycle. The latter are strongly influenced by the method used for normal shutdown of the CT/HRSG block. More extensive quantitative data and discussion related to transient tube-to-header temperature differences are provided in References 3 and 6.

3.4 Damage caused by the unintended presence of migrating condensate in the reheater during startups, shutdowns and onload operation

The unintended presence of condensate in RH and HPSH of HRSGs is difficult to detect without TCs attached to tubes. The magnitude of peak tube-to-tube temperature differences can vary widely and is impossible to quantify without installing thermocouples on a significant proportion of tubes in the most susceptible sections of the HRSG.

3.4.1 Condensate migration in RH2 during startup

Figure 10 plots the temperature measured at the top of every tube installed with a TC at their outlet just below the top outlet header during a cold HRSG start performed with the CT in ETM mode on 1-12-03. Steam flow was established through the reheater at about 28 minutes on Figure 10 and the introduction of pressure drop through the RH2 caused large quantities of condensate in lower manifold pipes and headers to be displaced forward through some of the tubes and into the RH2 outlet header.

Most of the condensate was displaced through the row 1 tubes as only three tubes of row 2 indicated sharp temperature drops at tube outlet when condensate migration occurred. However it was evident, (from other TC data not presented here), that condensate was present at the bottom of both row 1 and row 2 tubes during the same period.

To better appreciate the behavior of the condensate through the period when it was being blown forward, “Time Slice Data” (TSD) was prepared. Figure 11 is a typical TSD plot. Each TSD page plots on an arrangement drawing of RH2 tubes all RH2 tube temperatures measured by TC within the same time span of less than 5 seconds of each other by tube number, row number and position at top or bottom of tube, and plots each recorded temperature. Also highlighted on the RH2 tube & header symbolic arrangement drawing are the positions, relative to the numbered tubes, of the inlet and outlet pipe branches on the bottom inlet and top outlet headers, respectively, and the position of blind ends of each header.

Sequences of consecutive TSD plots were assembled at short time interval gaps for those periods when there was considerable instability or fluctuation in tube temperatures. For the period during the event plotted in Figure 10 when condensate was blown forward, 32 different TSD plots between 08:53 and 09:05 on 1-12-03 were assembled.

Figure 12 incorporates 6 of the sequenced 32 TSD plots for this start event to illustrate the large and rapid tube temperature fluctuations that occur when intermittently heated by gas and then chilled by slugs of condensate. Points for consideration relevant to Figs 10, 11and 12 are:

- The CT was synchronized and loaded to about 17MW at 08:44 hours; CT exhaust gas temperature was fixed and stable at about 700°F for several minutes before steam flow commenced through RH2.
- Prior to establishing a cooling steam flow through the RH2 tubes, the temperatures recorded at the top and bottom of rows 1 & 2 tubes align in general with reasonable expectations; i.e., row 1 tube top temperatures somewhat higher than and row 2 tube top temperatures and similarly row 1 tube bottom temperatures are generally above row 2 bottom temperature.
- Steam flow was established through the RH when the HRH steam dump control valve was opened between 08.53:30 and 08.53:45. The HRH steam startup vent remained closed throughout the startup
- Condensate blown up through tubes was most evident in the tubes closer to each of the four inlet pipe branches on the inlet header. Condensate blowing forward is initially evident at 08.53:45 through row 2 tubes 41, 42 and 43 opposite the 2nd RH2 inlet pipe branch downstream of the desuperheater and row 1 tube 53 opposite the 1st pipe branch after the desuperheater. By 08.54:00, (Figure 12), condensate was commencing to lower the bottom temperature of row 2 tubes 24 and 25 opposite the 3rd pipe branch. By 008.54:15, (Figure 12), condensate first became evident in tube 10 of row 2 and 15 seconds later tubes 7 to 11, opposite the 4th pipe branch from the blind end of the reheater interconnecting manifold, were at or close to saturation temperature either at their top or bottom TC.

Substantial quantities of condensate were blown forward over a period lasting more than 5 minutes. At some time points during the migration of condensate the temperature at the top of some tubes was chilled by up to 430°F below the other tubes which remained close to the gas temperature of about 700°F The average of top and bottom temperatures in some of the tubes chilled at bottom and top by condensate was transiently more than 300°F below that of adjacent tubes that remained free of condensate slugs. This develops very damaging thermal stresses, particularly at the weld attaching the offset row 2 tubes to the headers.

3.4.2 Gross condensate migration in RH2 during a warm restart

Figure 13 contains six TSD plots from a warm start from an initial HP drum pressure of 320psig on 3-13-03 using CT ETM with a setpoint for exhaust gas of 750°F when at CT minimum load.

CT firing commenced at 21.32. HPSH and RH drains were cycled open and closed several times between 21:32 and 21:38. The HP startup vent was cracked open throughout startup and the HRH startup vent was 20% open from 21:33 to 22:04. The HP bypass inlet pressure control valve (PCV) opened at 21.41:30 when HP pressure reached about 350psig. The HRH bypass PCV opened between 21.45:30 and 21.46:00 when the RH outlet pressure reached 150psig.

Immediately after the HRH bypass PCV opened and steam flow was established through the RH, condensate was blown through RH2 tubes for a period of about 10 minutes, Figure 13. Substantial quantities of condensate, initially sub-cooled, progressively flooded all tubes, commencing with tubes supplied by the 1st inlet pipe, then those supplied by 2nd, then 3rd and finally the 4th inlet pipe. Prior to this quenching incident, the top of tubes ranged between 700°F and 800°F. However, between 21.48:00 and 21.48:15 every top and bottom tube with a TC was between 340 and 400°F. During the incident, the temperature gradient in the ligament between some adjacent tubeholes through the outlet header was more than 400°F. In addition the average of top and bottom temperature of many tubes experienced a transient tube-to-tube temperature difference of about 240°F.

Such severely damaging events cannot be detected from normal DCS data and similar condensate quenching incidents have probably occurred on many HRSGs.

In this incident, it is improbable that condensation inside tubes or pipes of the RH was anything more than a minor contributor to the large quantity of condensate that was in the RH for so long after HRH steam flow was established. In tests on this and other HRSGs, three potential sources of condensate carry over into the RH during starts have been identified:

1) Reverse flow in the RH drains and of blowing slugs of condensate from the blowdown vessel into the RH interconnection manifold, lower headers and tubes. HPSH and RH drains need to be open simultaneously during all CT starts. When HPSH and RH drains are disposed to the same blowdown vessel, the large flow of HPSH drains sometimes raises the vessel pressure above RH pressure On most horizontal gas path HRSGs, there is inadequate static head to quickly drive the RH drains into the vessel, even when both RH and blowdown vessel are both at atmospheric pressure.
2) Leakage of attemperator spraywater when intended to be shut off. Interlocks should ensure that the spraywater block valve cannot be opened unless CT exhaust gas temperature is above a minimum setpoint temperature below which desuperheating is never required. Frequent maintenance of attemperator spraywater control and block valves is essential to maintain tight shutoff capability during CT starts and initial loading.
3) Carryover of condensate from cold reheat pipes into RH1; long, large diameter pipes condense substantial quantities of vapor during starts. Inadequate drainage arrangements, such as too small drain lines, reliance on reverse flow of condensate to drain connections against steam flow direction, inadequate static head and/or disposed to the same blowdown vessel as HPSH drains, etc. are all too common. The second source of large amounts of condensate in cold reheat pipes is leakage of HP bypass attemperation spraywater, due to inadequate protective interlocks, malfunction and/or inadequate maintenance to preserve tight shutoff.

All of the foregoing potential causes of severely damaging condensate migration in the RH (and similarly in the HPSH) tubes can be avoided by more diligent design and improved operating and maintenance practices.

3.4.3 Tube temperature differences caused by RH2 attemperator spraywater overspray to below saturation temperature during starts.

A warm restart was executed at about 22:30 on 3-11-03 - less than 1 hour following a trip from 18MW. The RH desuperheater sprayed down to saturation temperature between about 02:21 and 03:05 on 3-12-03 because RH outlet steam temp set point was lowered to about 950°F during the period when the CT was ramped up from 16MW to 100MW and CT exhaust gas temperature raised from about 770°F to 1200°F; Figure14.

There is pressure on the operator to expedite loading of the CT and the raising of pressure during startups to meet the short "out of compliance" time limits set by regulatory permit. It is difficult or impossible for any desuperheater to control steam temperature under these rapidly changing conditions. During this set of events the following conditions occur simultaneously:

- CT exhaust temperature is rising rapidly.
- Steam flow decreases as HP pressure increases since most or all of the evaporation is required to compress the volumes occupied by steam in drum, HPSH tubes and piping.
- The rise in steam temperature through RH1 and RH2 is very high because steam flow is reduced (while raising HP pressure), yet heat input from rapidly increasing CT exhaust gas temperature and flow increases rapidly.
- Additional RH desuperheater spraywater is needed, but the reduced steam flow degrades the RH desuperheater's effectiveness.

Under the above conditions it is not unusual for RH and/or HPSH steam outlet temperature to exceed design limits for a short time. While the outlet header experiences some accelerated creep life consumption, the damage would be insignificant if the duration of the event were kept short, especially when pressure is low.

The subject RH is equipped with an instantaneous high outlet steam temperature trip mandated by the jurisdiction's National Board Inspector. In an effort to avoid this trip the operators are tempted to lower the RH outlet steam temperature set point during the CT load increase transient that takes exhaust gas temperature to its maximum of 1200°F. If the setpoint is lowered too much, an overspray condition is inevitable. Far more damage is done to the RH (and HPSH) by quenching from the overspray event than would be caused if the design RH steam temperature were intermittently exceeded. This is just one example where poorly thought out regulatory limits, (short startup times, overly conservative high steam temperature trips that give no consideration to the much more severely damaging consequences), sometime create a significantly bigger problem than the one being solved. Transients like this one are much better handled by automation that eliminates the need, if not the ability, for the operator to take things into his own hands.

Overspraying, (to about 50°F below RH saturation temperature of about 350°F according to the permanent thermocouple in the RH interconnecting manifold downstream of the desuperheater water injection nozzle) occurred for about 40 minutes, Figure 14

Figure 15 highlights the very poor mixing of the spraywater with steam. A disproportionate amount of desuperheating water travels to the blind end of the manifold and all row 1 and row 2 tubes supplied by steam through the 4th inlet pipe branch at the blind end of the manifold are at about 350°F, which is saturation temperature at the prevailing RH pressure. Some of the tubes supplied with steam from the three preceding pipe branches off the manifold are at saturation temperature, but the majority of those tubes measured are between 100 and 270°F above saturation temperature. The temperature at the outlet of RH2 tubes closest to the desuperheater operate at higher temperature than those supplied by a pipe branch further away from the desuperheater. Some tubes are more than 150°F hotter than other adjacent tubes.

HPSH and RH outlet temperature setpoints should not be lowered significantly below their design value of 1050°F, as it can result in damaging tube-to-tube temperature differences when the resulting outlet temperature from either the HPSH or RH the desuperheater is too close to saturation temperature.

3.4.4 Tube temperature differences caused by RH2 attemperator spraywater overspray to below saturation temperature during CT deloading prior to shutdown.

A similarly severe overspray event was recorded during both the startup and shutdown performed on 3-14-04, (figure 16). Note the sudden drops in RH desuperheater outlet temperature. The steam temperature drop on the left is during startup, similar to that in figure 14, while the steam temperature drop on the right is during shutdown. This overspray event again occurs when the gas turbine load transitions the range below 100 MW in which exhaust temperature is still at the isothermal maximum while the steam flow rate is simultaneously reducing.

The CT was deloaded rapidly from 178MW to about 110MW at 10%/min, followed by a hold of about 20 minutes, followed by another rapid load reduction to 40MW at 10% per minute. Load was then reduced progressively using ETM to maintain a linear fall in CT exhaust gas temperature from about 1200°F to about 700°F over about 60 minutes (about 8.3°F/min).

HRH steam temperature setpoint was maintained throughout the shutdown a few degrees below nominal design temperature of 1050°F. Nevertheless, the deloading at 10%/min from baseload to 110MW, and even more so after the hold at 110MW down to 40MW at 10%/min, caused heavy RH attemperation and unstable desuperheater control (overspray event on right side of Figure 16). Figures 17, 18, 19 and 20, which plot all tube temperatures with a TC for; row 1-top; row 2-top; row 1-bottom; and row 2-bottom, respectively, highlight the very non-uniform distribution and significant tube-to-tube temperature differences.

3.4.5 Incomplete Attemperator Vaporization - Steady State on-load operation

While the previous examples of temperature transients can be avoided by thoughtful design and operation it is often easier said than done. This is due to the difficulty in effectively coordinating the combustion turbine's characteristics, HRSG design, superheater/reheater drain system design, startup time requirements, operating procedures, and last but not least - project cost and schedule. Having said that, the following example of differences in temperatures between tubes during steady state operation should not be encountered with a properly designed and installed attemperator.

Figure 21 presents a TSD plot during full load (179 MW) steady state operation with no RH attemperation. The temperature at the bottom of almost every tube in both RH2 tube rows across the duct width was within +/-5°F of 940°F. Temperature at the top outlet of row 1 tubes ranged between 1035 and 1045°F, and of row 2 tubes between 1020 and 1030F. RH steam outlet header temperature was about 1028°F, which aligns closely with the mean of all RH2 row 1and row 2 tube temperatures. The mean temperature at outlet of row 1 tubes is about 15°F higher than row 2 tubes and the difference in average temperature between row 1 and row 2 tubes is thus about 7.5°F, which is of no concern. Figure 21 demonstrates satisfactory uniform heating across RH2 when it receives steam at a uniform temperature from the interconnecting manifold below, (Figure 3).

Figure 22 presents a TSD plot at 04:00 on 3-12-03 during stable operation at 110MW with HRH header temperature of 1,042°F and desuperheating of about 85°F. The bottom of all tubes supplied by the 3rd and 4th RH2 inlet pipe branches operate very close to 900°F, except for three Row 1 tubes that are about 30°F hotter. The bottom of all tubes supplied from the 1st and 2nd pipe branch downstream of the desuperheater operate at about 745°F and about 845°F, respectively; i.e., respectively about 155°F and 55°F lower than the bottom of the tubes supplied by the two pipe branches furthest from the desuperheater. The variation in temperature at outlet of tubes supplied by the different inlet pipes is about 20% of the differences measured at the bottom of the tubes.

The most significant differences in the average of top and bottom temperature occur in the RH2 panel assembly supplied by the 1st and 2nd inlet pipes. At 04:00, the average temperature of row

1 and row 2 tubes supplied by the 2nd pipe branch is about 968°F and 945°F, respectively, whereas the average of Row 1 tubes supplied by the 1st inlet pipe is about 903°F. No TCs were installed at the top of Row 2 tubes supplied by the 1st inlet pipe, but assuming that the top of these tubes is 50°F lower temperature than their corresponding Row 1 tubes, (as is the case with the Row 1 and 2 tubes supplied by the 2nd pipe), then the average of top and bottom temperatures for the Row 2 tubes supplied by the 1st pipe is estimated to be 878°F, (about 90°F lower than the highest temperature tubes attached to the same headers).

The wide variation in RH2 tube outlet temperatures results in some tubes and header tubeholes operating at about 1110°F, at a time when the unit was producing steam at 1042°F, below its design HRH steam temperature.

Figure 23 presents a TSD plot at 03:05 on 5-8-04 during steady state operating conditions at a typical overnight load (85MW) with the attemperator producing a 164°F drop in steam temperature from its inlet to outlet. Note that as the attemperator injects more spray water the differences between bottom tube temperatures become even more pronounced. Also note that the upper temperature of many tubes on the left side of the reheater are at or above the header's design temperature of 1082°F. It should follow that portions of the header where these tubes attach are also operating above design temperature. This does not bode well for this header’s creep life consumption.

4 Rapid Cooling of Headers - Borehole Cracking

As was previously noted (Figure 9), the greater the wall thickness of an HPSH or RH higher temperature header the more sluggish is its response to internal fluid temperature changes. Thicker headers must be heated significantly slower than thin headers during starts. Of even greater concern, rapid cooling by sub-cooled condensate of the tubeholes and header bore of thicker higher temperature headers causes severe tensile stresses that will lead to cracking at the intersection of the tube holes and header bore. This failure mechanism has been documented in numerous conventional plants around the world with headers of similar proportions to those in many HRSGs. There is no reason to believe HRSGs will not suffer the same consequences if temperature transients affecting the headers are not carefully managed.

5 Recommendations

- HRSG design issues
    - Use panels with a single tube row per upper and lower header pair in superheaters and reheaters to eliminate additional bending stresses at offset tube – to – header welds.
    - 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.
    - Ensure that SH and RH drain systems quickly and reliably remove all condensate from tubes, lower headers, pipes and manifolds. The “worst case” for sizing drain pipes and valves is generally at atmospheric pressure.
    - Route RH drains and HPSH drains to separate blowdown vessels to prevent pressurizing of vessel above RH pressure during startup.
    - Ensure that under cold and hot operating conditions that all lower manifolds, interconnecting pipes, drain pipes, etc, have fall in the direction of normal flow.
    - Provide large drains on cold reheat pipes before the HRSG to remove substantial condensate formed during cold starts and to dispose of any spraywater leakage at the HP bypass attemperator.
    - Automate RH and HPSH drain control and block valves during starts and shutdowns

- Select RH and HPSH outlet design temps above baseload operating conditions to accommodate over temperature excursions during simultaneous ramping of CT and HP pressure
- Request changes to design code to permit limited periods of operation above, by a moderate amount, the nominal design temperature, since short periods of accelerated creep (with reduced pressure stresses) are much less damaging than the rapid life expenditure caused by overspraying in desuperheaters, (provided the high-high temp limit is well below material transformation temperature).

- CT design influences
  - 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.

- 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 minimize tube-to-header temperature differences

- 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

  - Maintain high HP drum pressure during CT/HRSG shutdown prior to an overnight or weekend shutdown such that HPSH and RH headers are as warm as possible at the next startup to minimize the peak tube to header temperature difference.

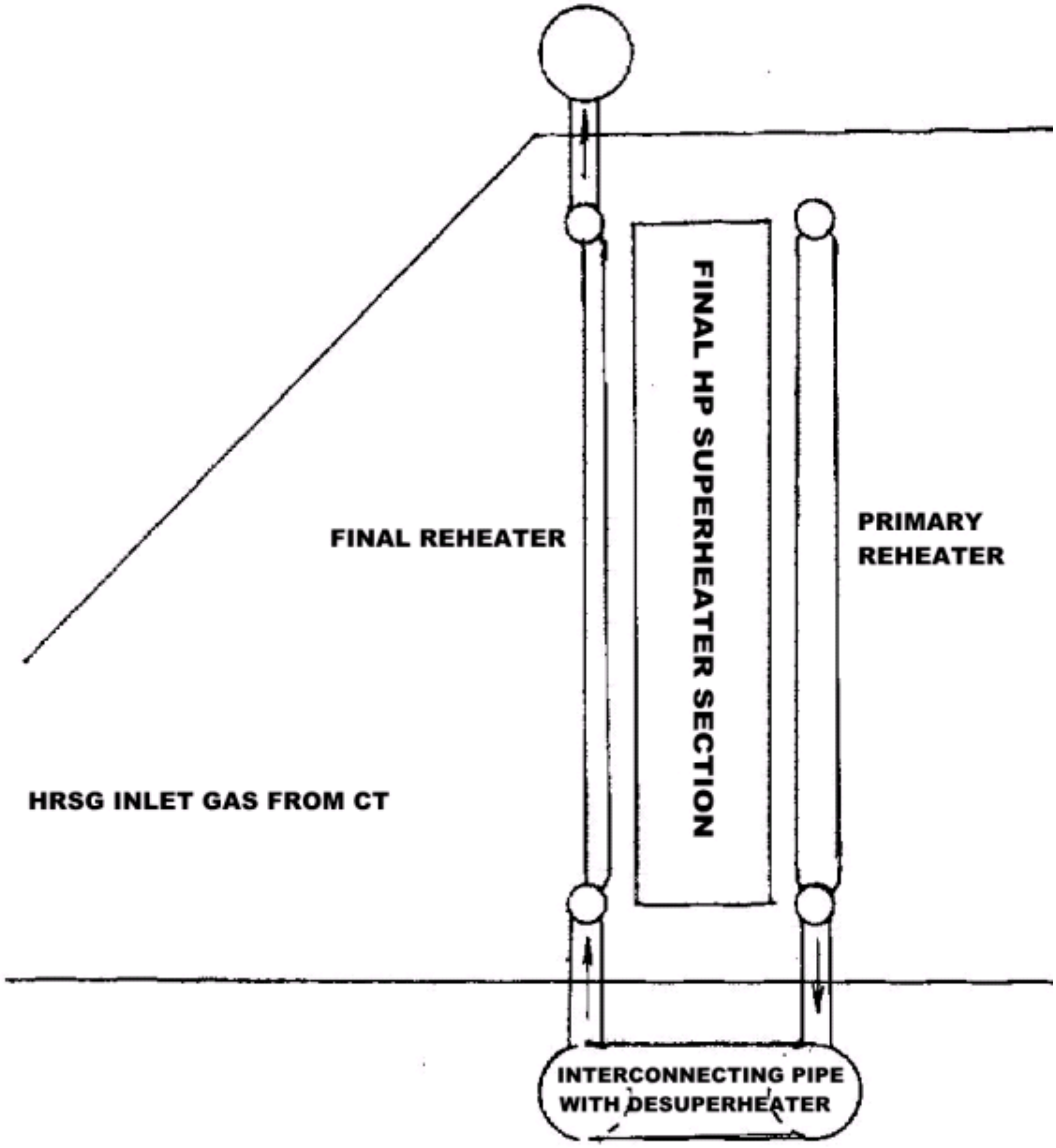

FINAL HP SUPERHEATER SECTION
FINAL REHEATER
PRIMARY
REHEATER
HRSG INLET GAS FROM CT
INTERCONNECTING PIPE
WITH DESUPERHEATER

Figure 1

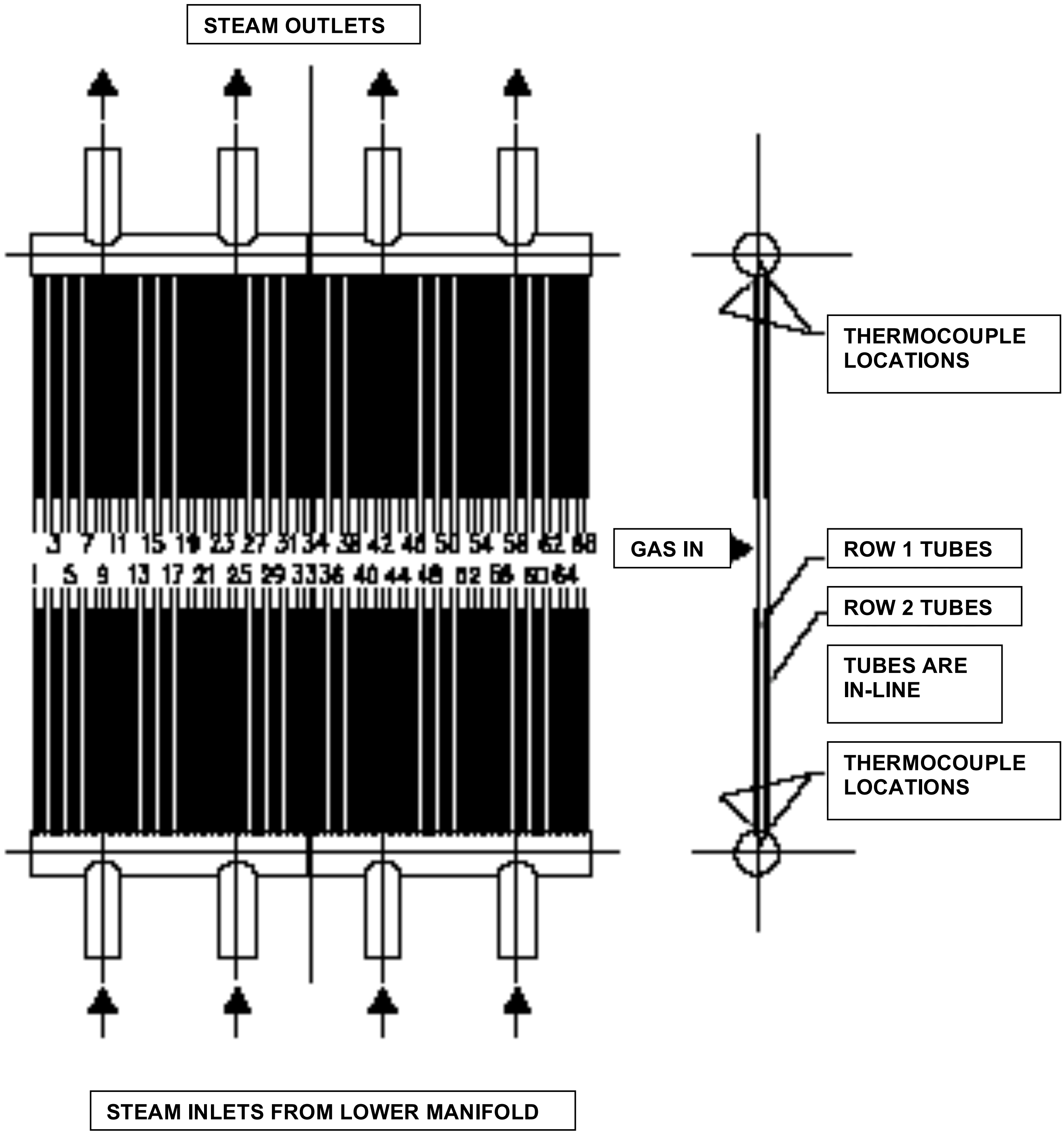

STEAM OUTLETS
THERMOCOUPLE LOCATIONS
GAS IN
ROW 1 TUBES
ROW 2 TUBES
TUBES ARE IN-LINE
THERMOCOUPLE LOCATIONS
STEAM INLETS FROM LOWER MANIFOLD

Figure 2

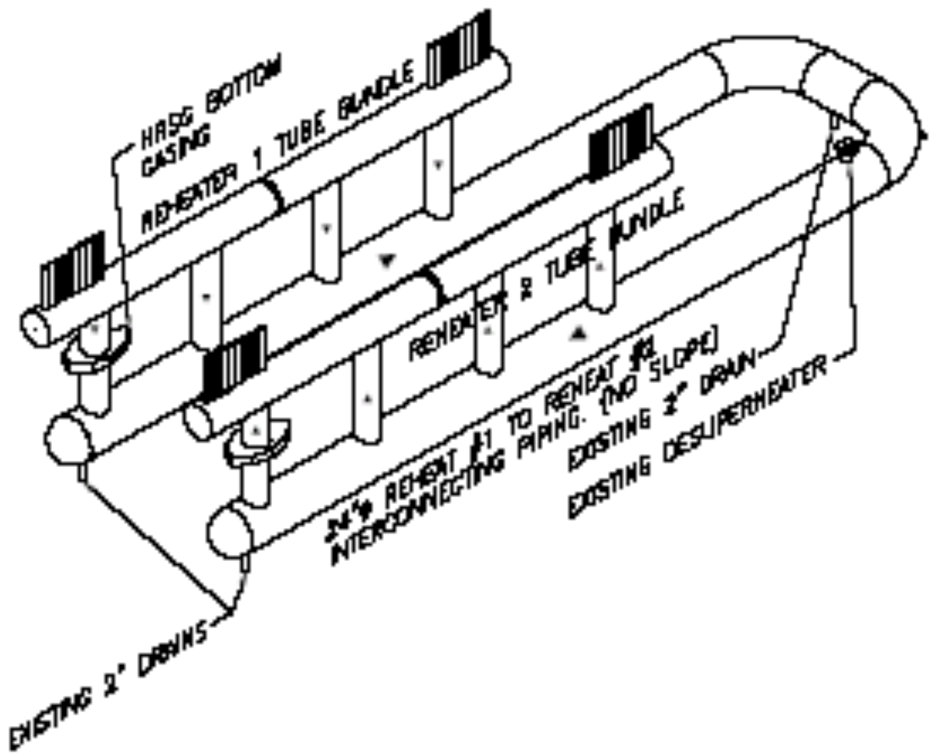


Figure 3

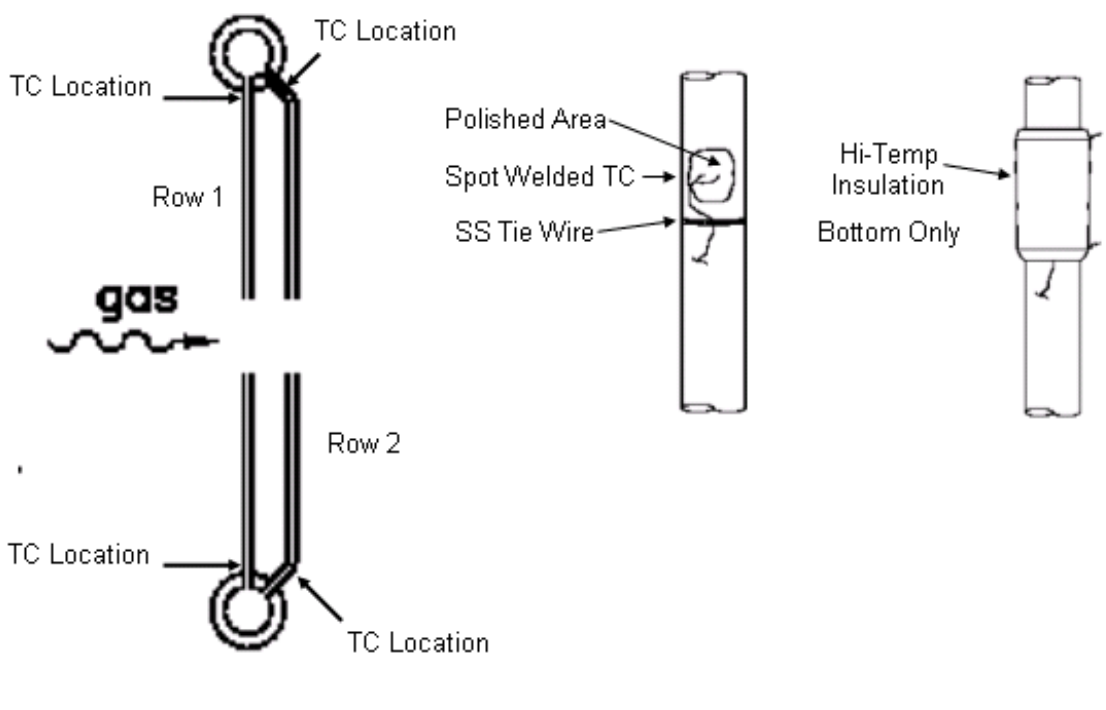


Figure 4

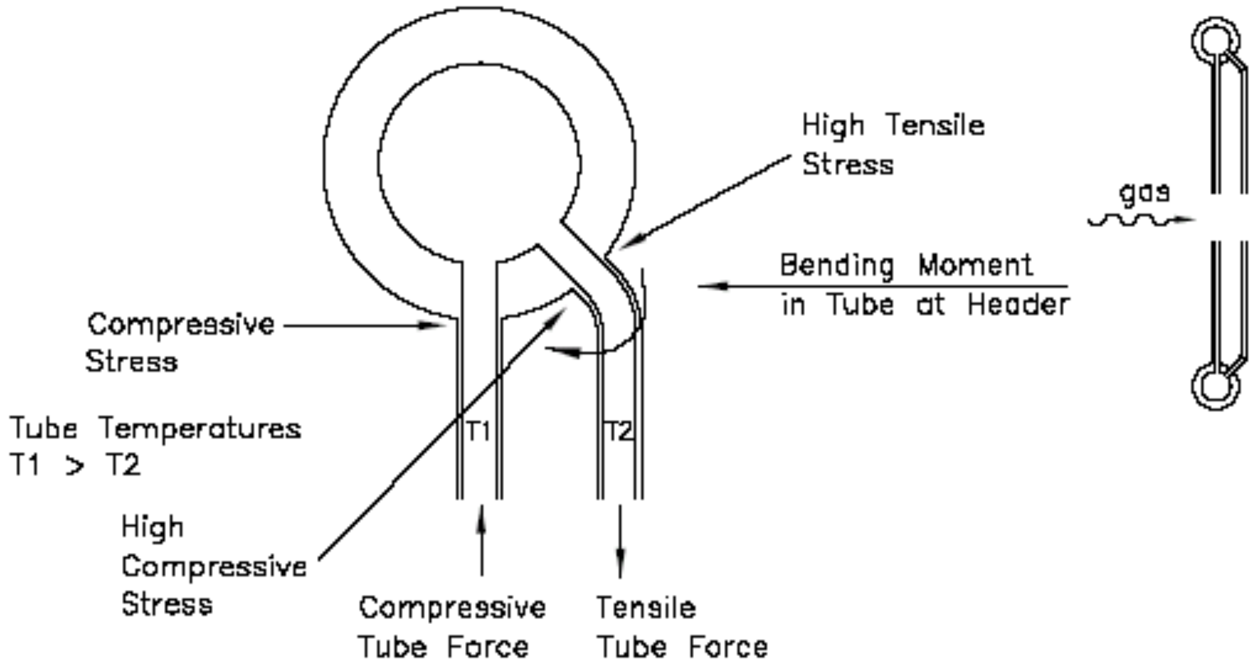


Figure 5

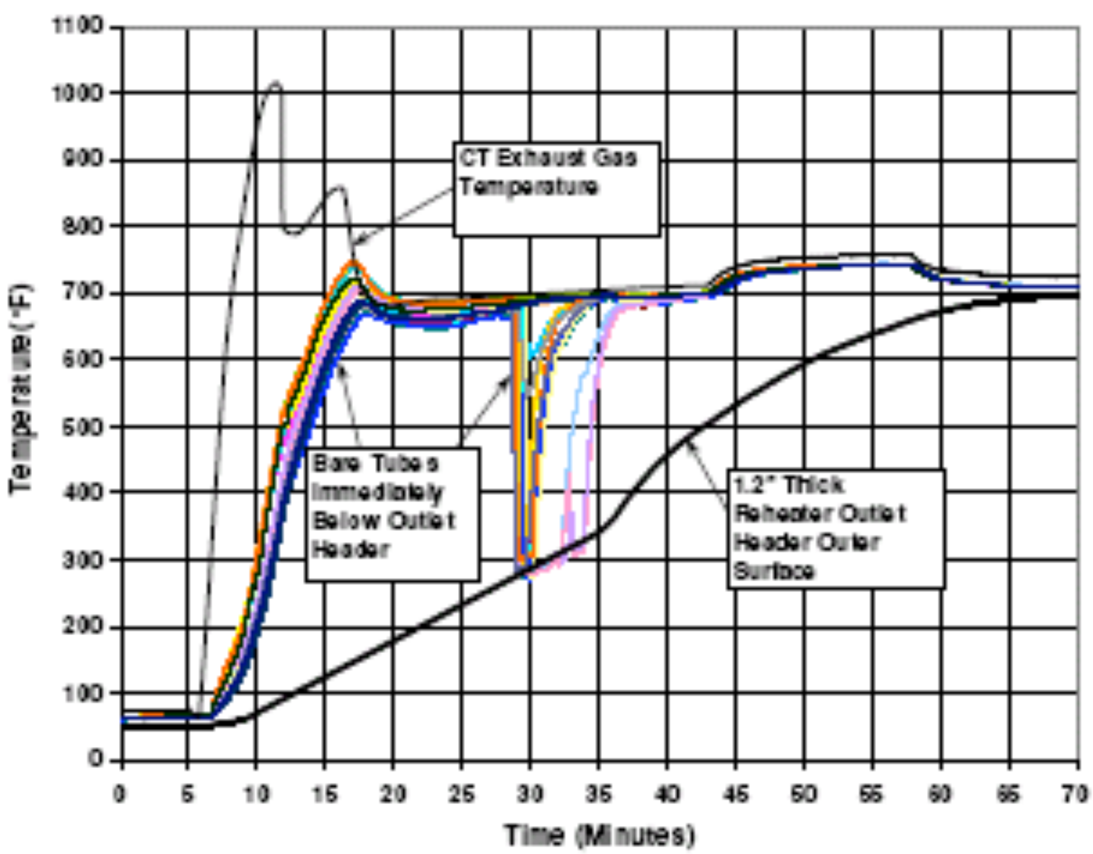


Figure 6

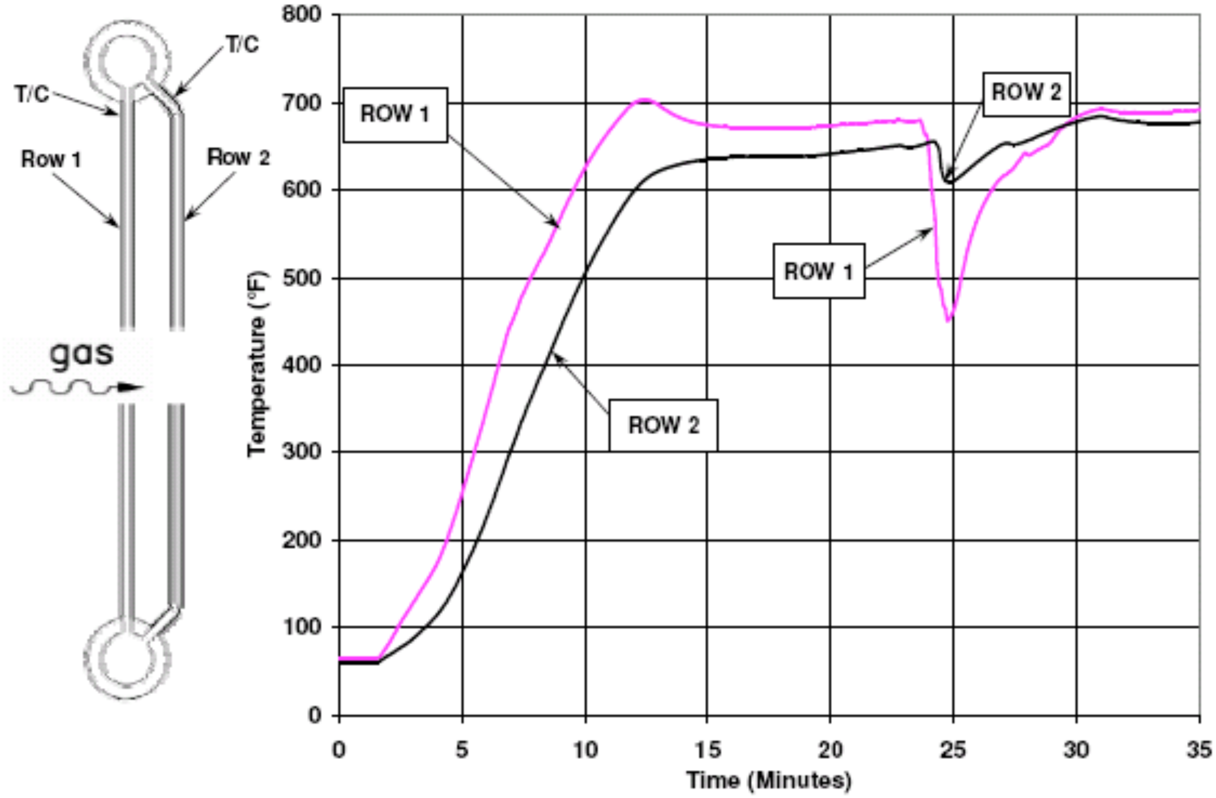


Figure 7

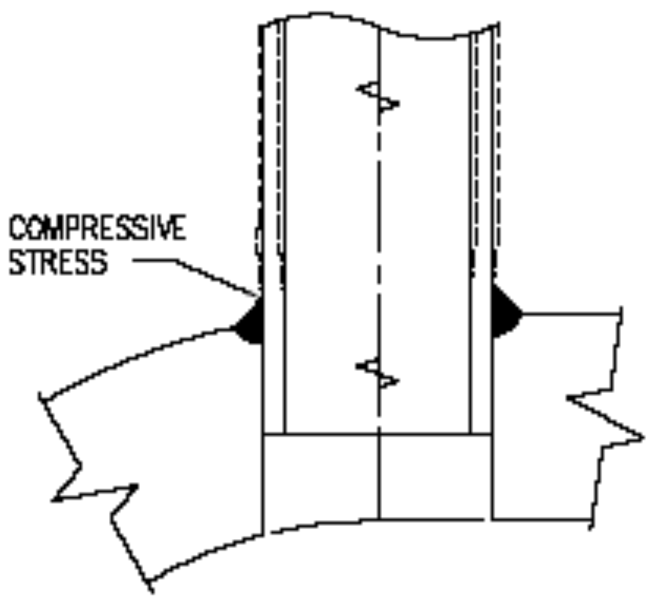


Figure 8

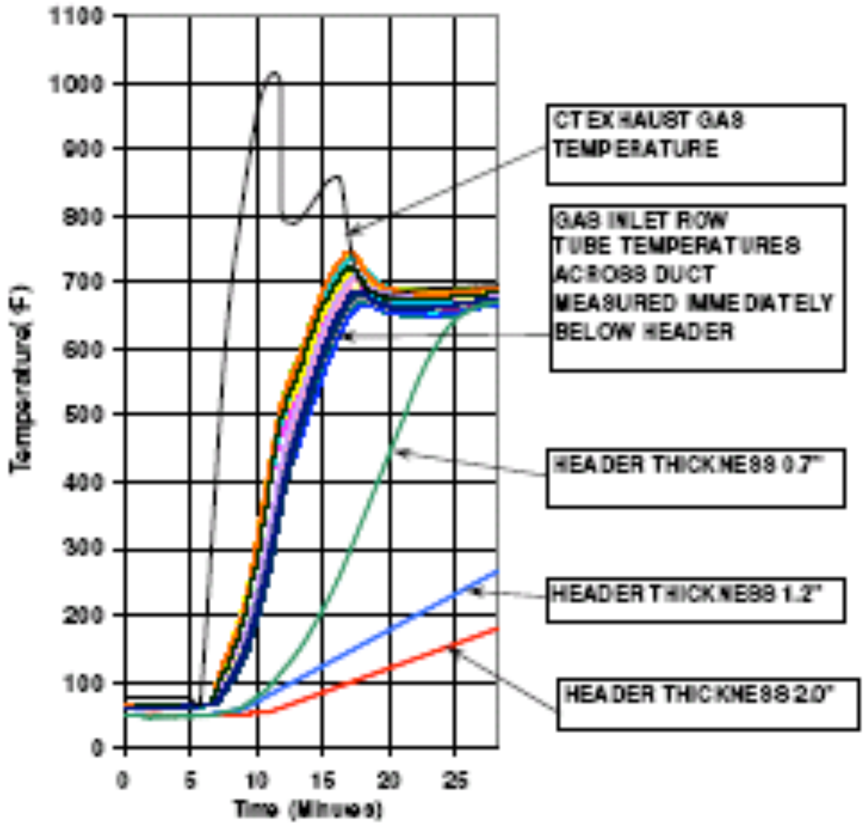
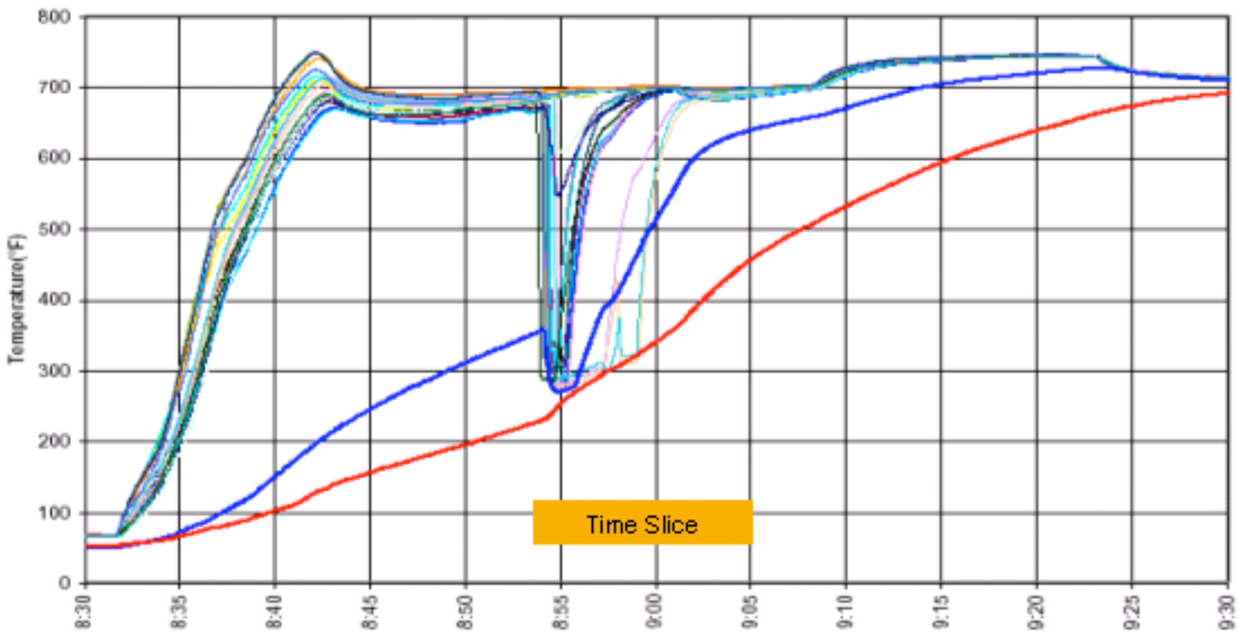


Figure 9



Cold Start

Figure 10

Cold Start 1-12-03 Time Slice Data

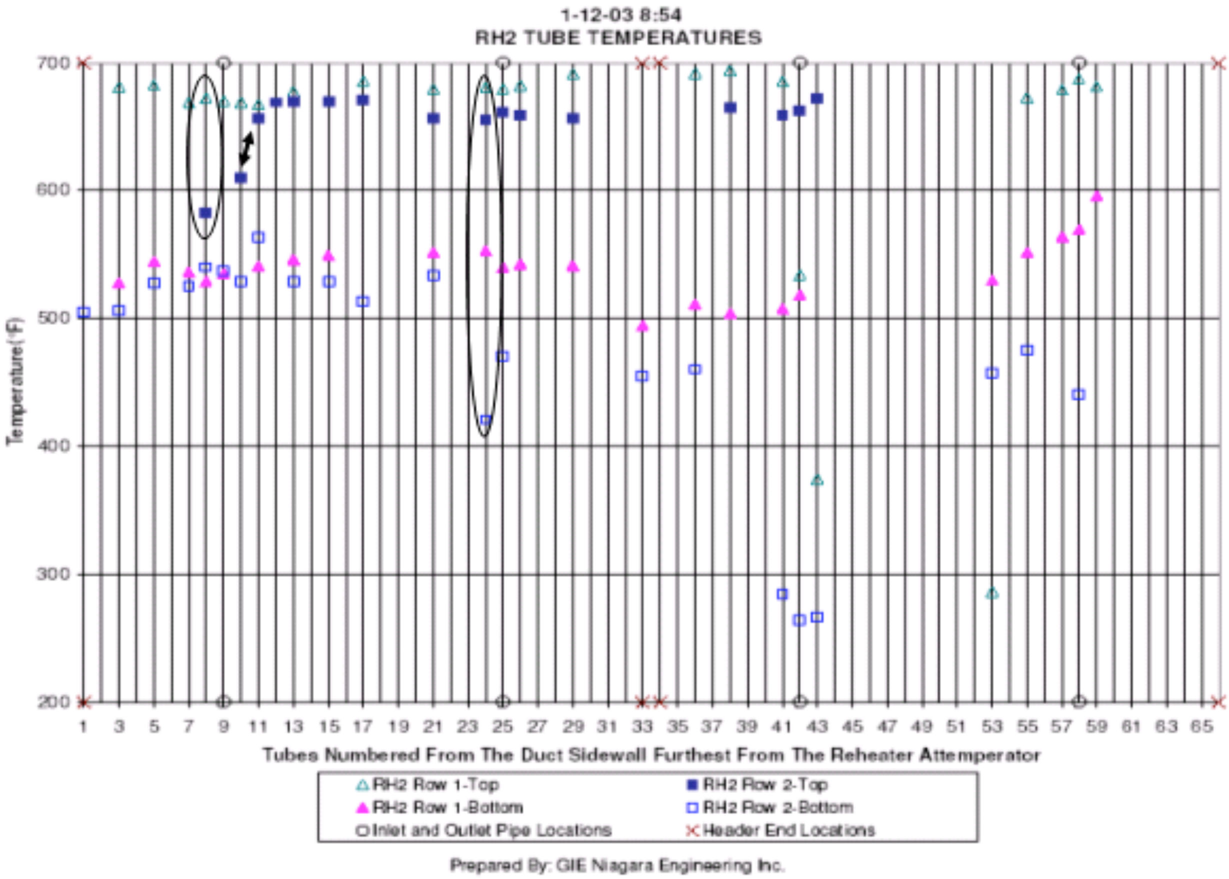


Figure 11

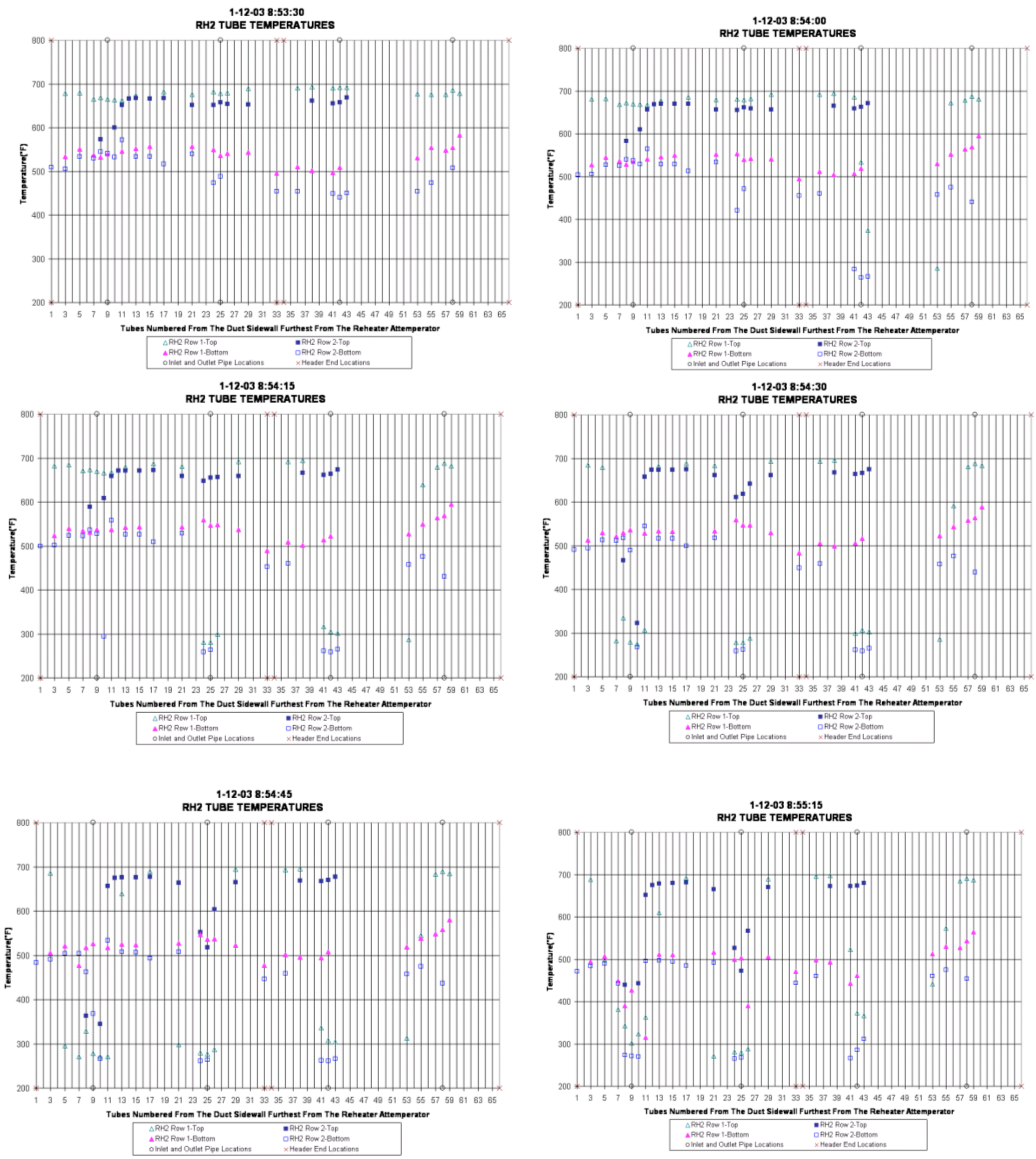

1-12-03 8:53:30
RH2 TUBE TEMPERATURES
1-12-03 8:54:00
RH2 TUBE TEMPERATURES
1-12-03 8:54:15
RH2 TUBE TEMPERATURES
1-12-03 8:54:30
RH2 TUBE TEMPERATURES
1-12-03 8:54:45
RH2 TUBE TEMPERATURES
1-12-03 8:55:15
RH2 TUBE TEMPERATURES
Temperature(°F)
Tubes Numbered From The Duct Sidewall Furthest From The Reheater Attemperator
RH2 Row 1-Top
RH2 Row 2-Top
RH2 Row 1-Bottom
RH2 Row 2-Bottom
Inlet and Outlet Pipe Locations
Header End Locations

Figure 12

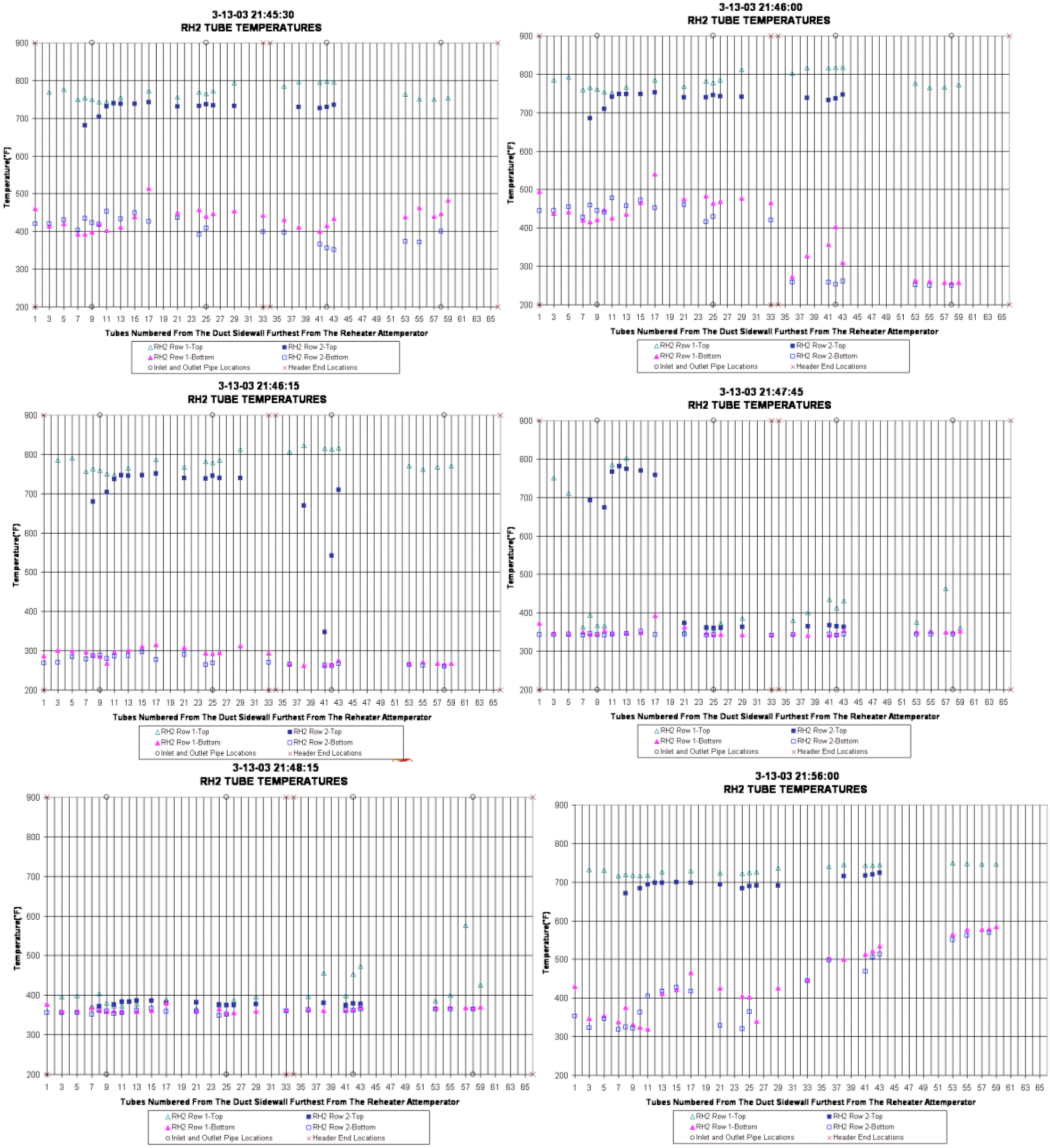

3-13-03 21:45:30
RH2 TUBE TEMPERATURES
3-13-03 21:46:00
RH2 TUBE TEMPERATURES
3-13-03 21:46:15
RH2 TUBE TEMPERATURES
3-13-03 21:47:45
RH2 TUBE TEMPERATURES
3-13-03 21:48:15
RH2 TUBE TEMPERATURES
3-13-03 21:56:00
RH2 TUBE TEMPERATURES
Temperature(°F)
Tubes Numbered From The Duct Sidewall Furthest From The Reheater Attemperator
RH2 Row 1-Top
RH2 Row 2-Top
RH2 Row 1-Bottom
RH2 Row 2-Bottom
Inlet and Outlet Pipe Locations
Header End Locations

Figure 13

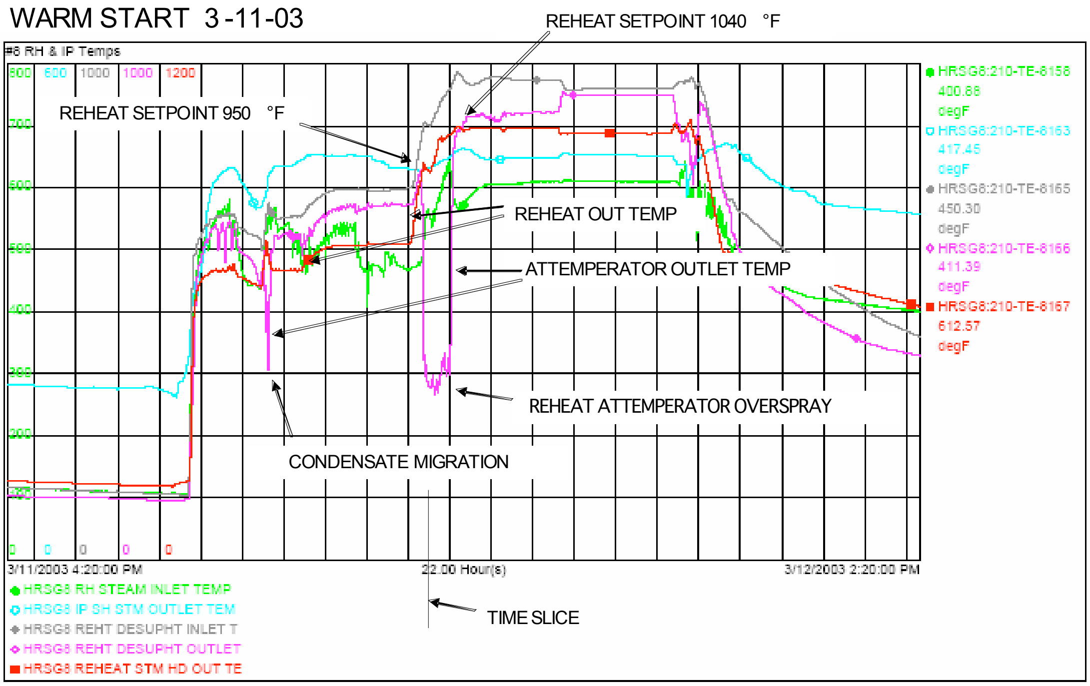


Figure 14

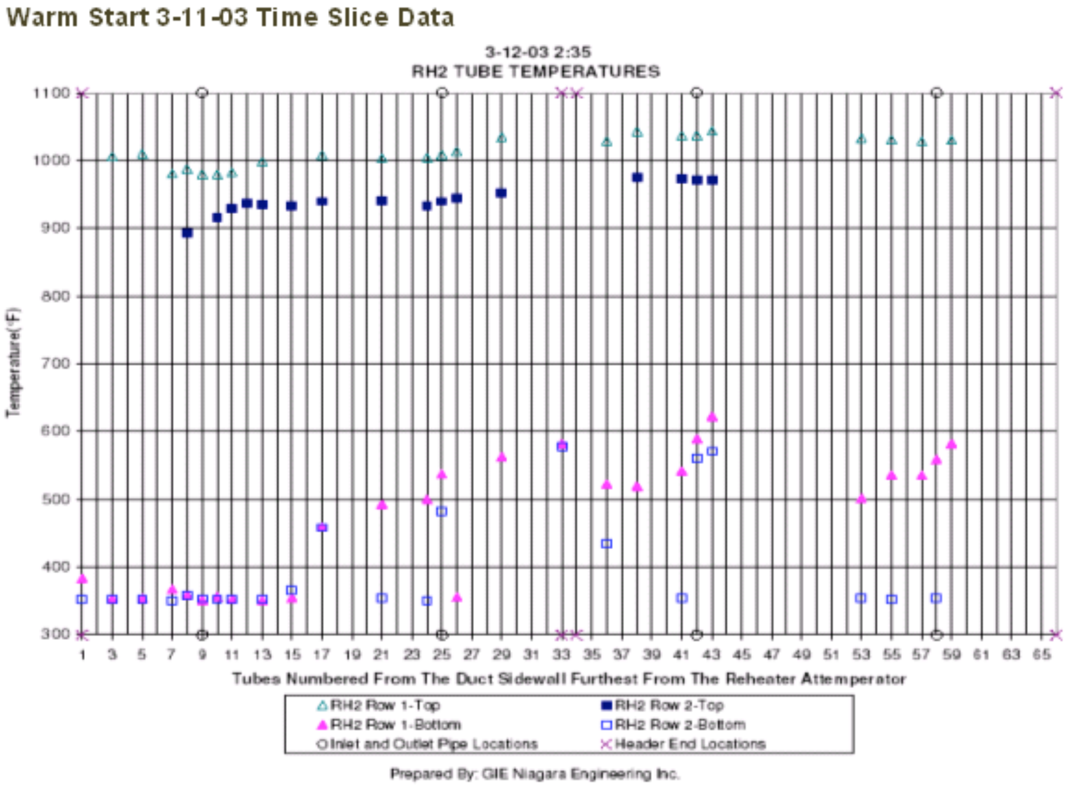


Figure 15

SHUTDOWN 3 -14-03

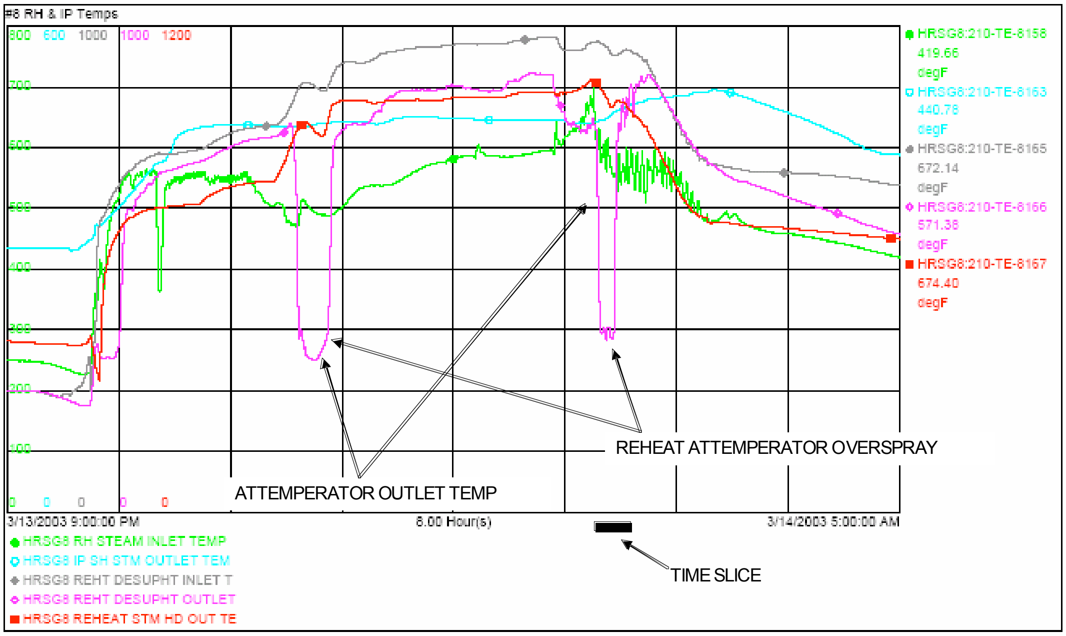
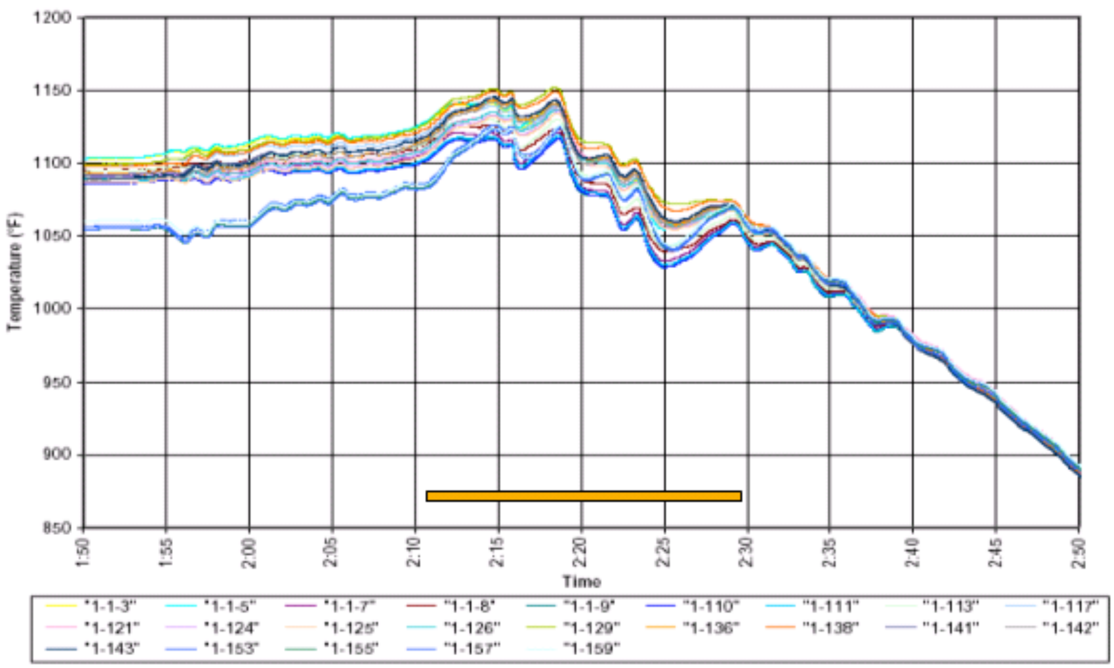


Figure 16

Shutdown 3-14-03 Top of Row 1 Tubes



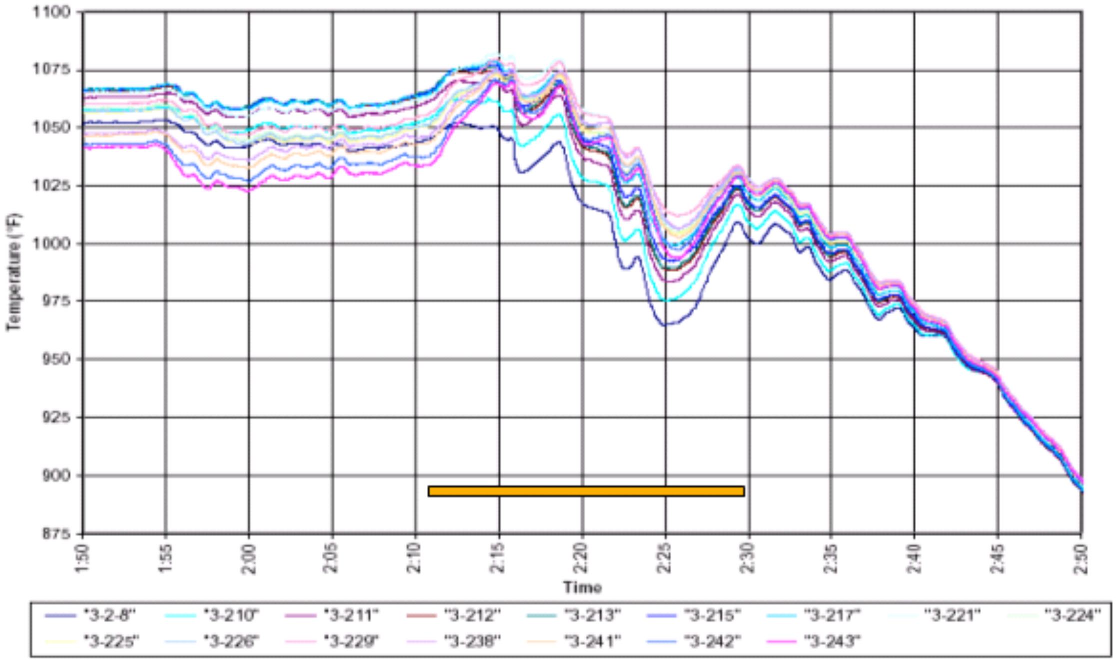
File: RH2-1-Top
Tab: Chart1

Prepared By:
GIE Niagara Engineering Inc.

Sheet
1 of 1

Figure 17

Shutdown 3-14-03 Top of Row 2 Tubes



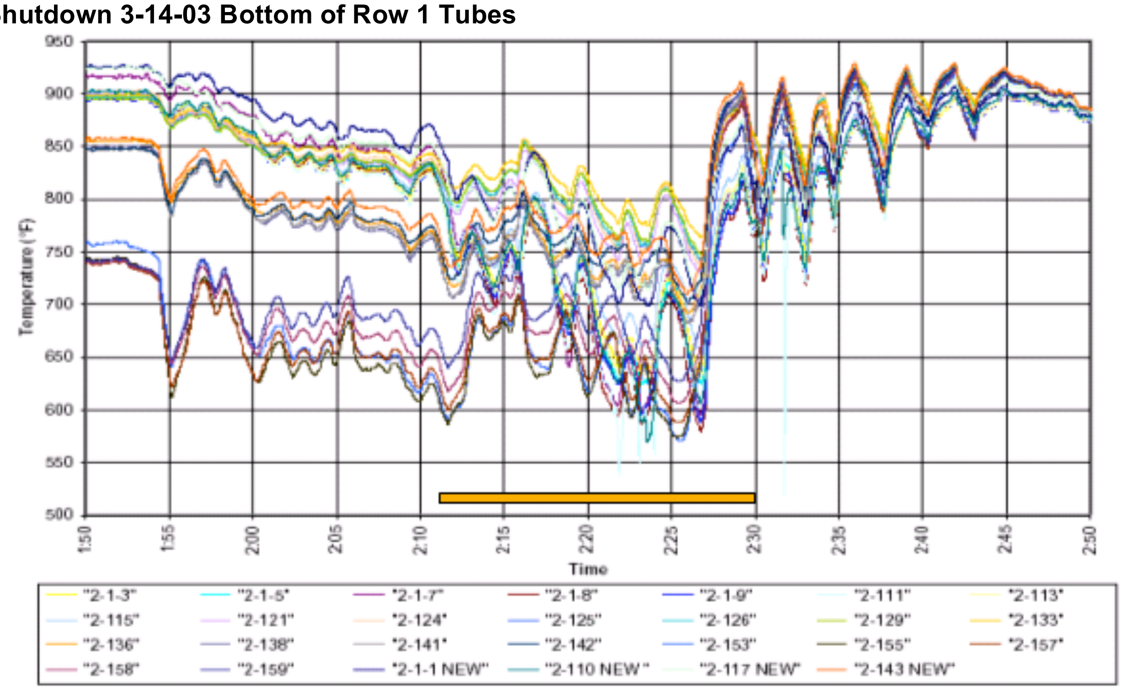
File: RH2-2-Top
Tab: Chart1

Prepared By:
GIE Niagara Engineering Inc.

Sheet
1 of 1

Figure 18

Shutdown 3-14-03 Bottom of Row 1 Tubes



File: RH2-1-Bottom
Tab: Chart1

Prepared By:
GIE Niagara Engineering Inc.

Sheet
1 of 1

Figure 19

Shutdown 3-14-03 Bottom of Row 2 Tubes

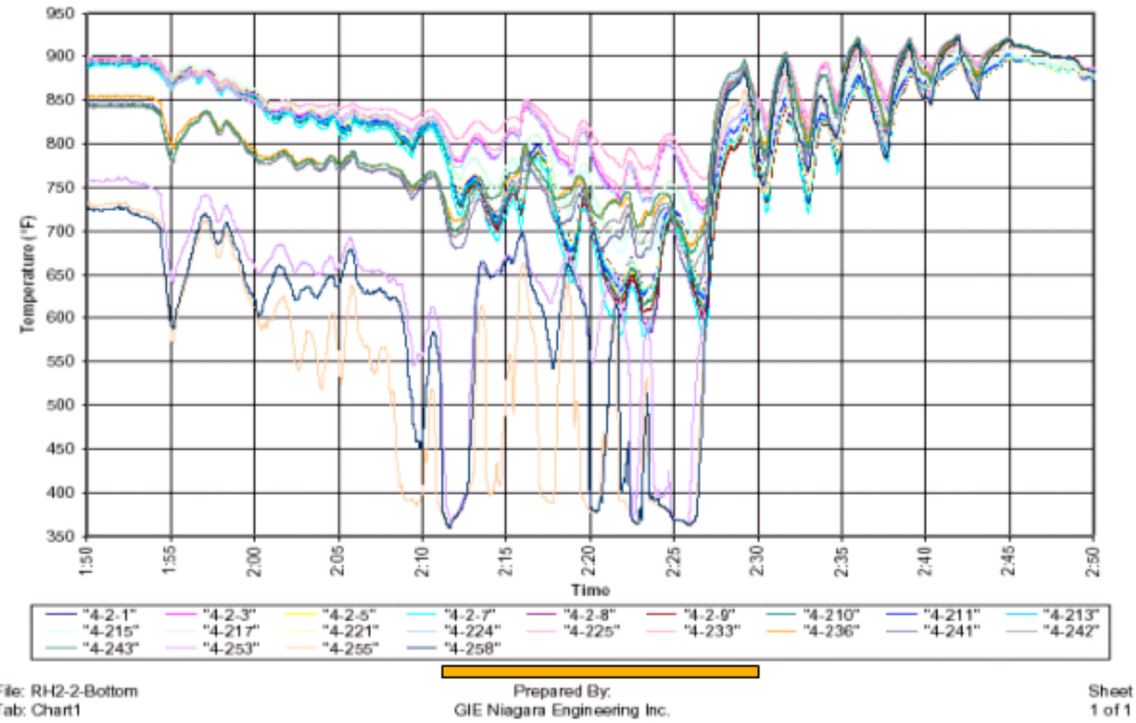


Figure 20

Steady State Data @ 179MW with No Attemperation – RH Steam Outlet Temp 1029°F

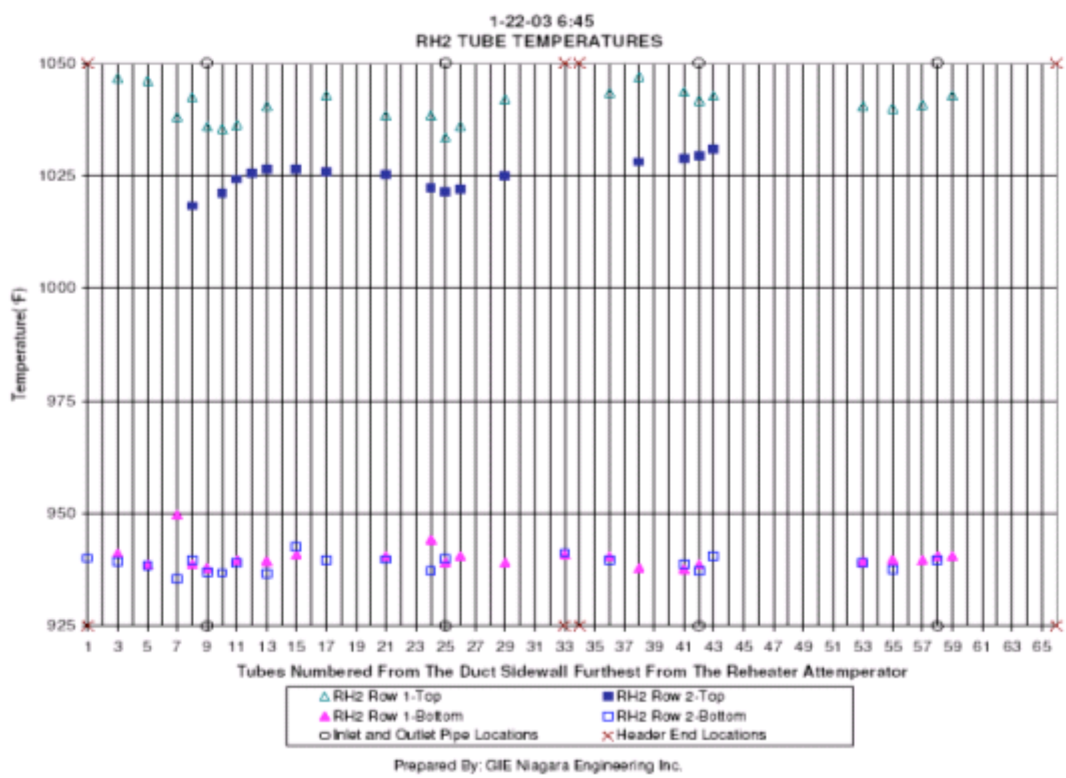


Figure 21

Steady State Data @ 110MW with 79°F Attemperation – RH Outlet Steam Temp 1046°F

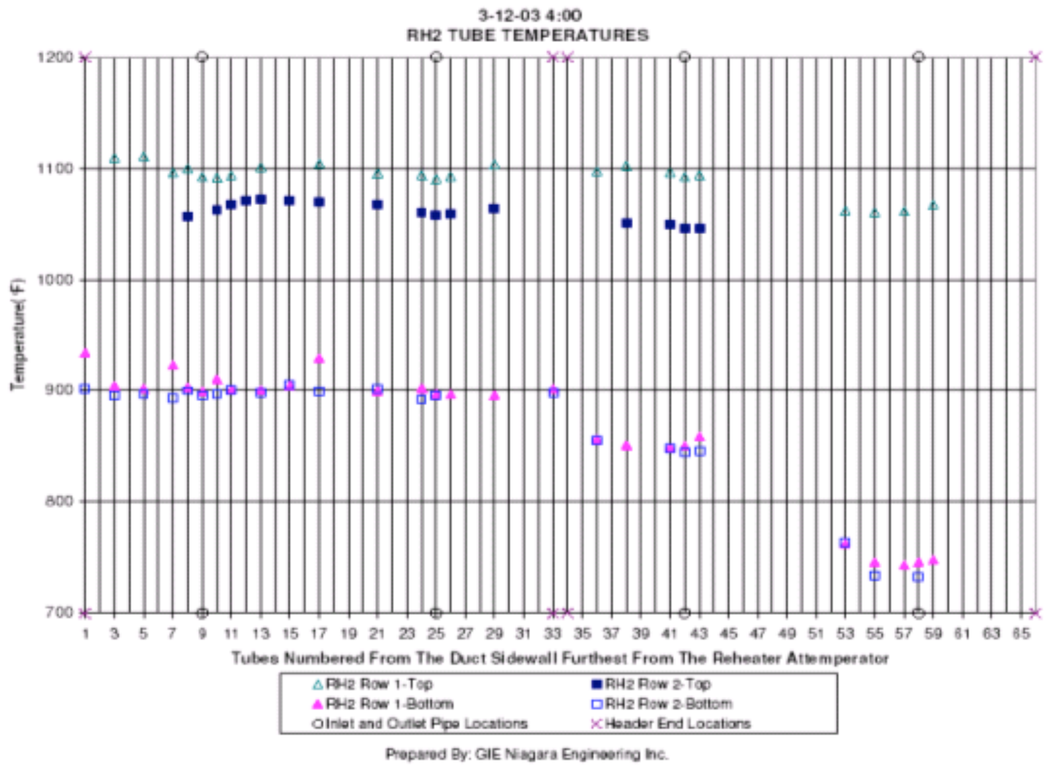


Figure 22

Steady State Data @ 85MW with 164°F Attemperation – RH Outlet Steam Temp 1028°F

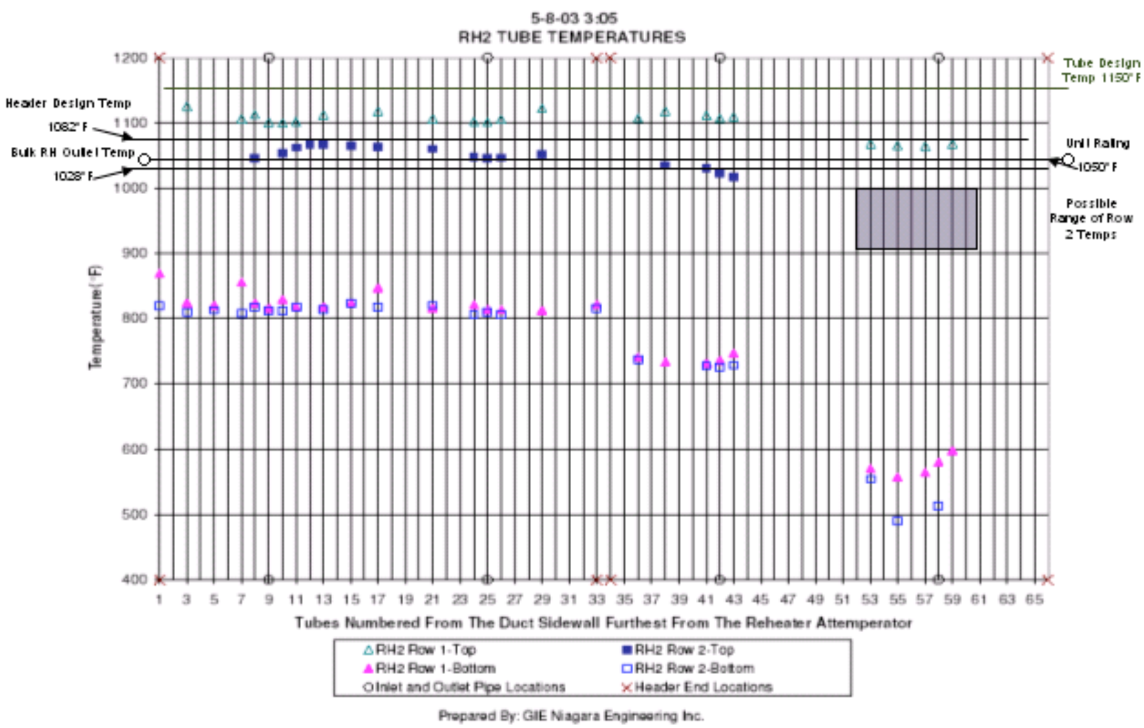


Figure 23

References

1. Pearson, J.M., Anderson, R.W., “Reliability and durability of large heat recovery steam Generators”, *Proceedings of Institution of Mechanical Engineers, (U.K.),* Volume 213, Part A, pp151-168.

2. Pearson, J.M., Anderson, R.W., “Root causes of transient tube temperature anomalies measured in horizontal gas path HRSGs”, *EPRI International Conference on Boiler and HRSG Tube Failures and Inspections”* Phoenix, Arizona, November, 2001.

3. Pearson, J.M., Anderson, R.W., “Influences of HRSG design and operation on the durability of two-shifted HRSGs”, *European Technology Development Conference on HRSG Technology,* London, November, 2003.

4. Dooley, R.B., Paterson, S.R., Pearson, J.M., “HRSG Dependability”, *European Technology Development Conference on HRSG Technology,* London, November, 2003.

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

6. Dooley, R.B., K.J. Shields, S.R. Paterson, T.A. Kuntz, W.P. McNaughton, M. Pearson, and R. Sirois, *Delivering High Reliability Heat Recovery Steam Generators*, TR-1004240, EPRI, Palo Alto, CA. 2003.