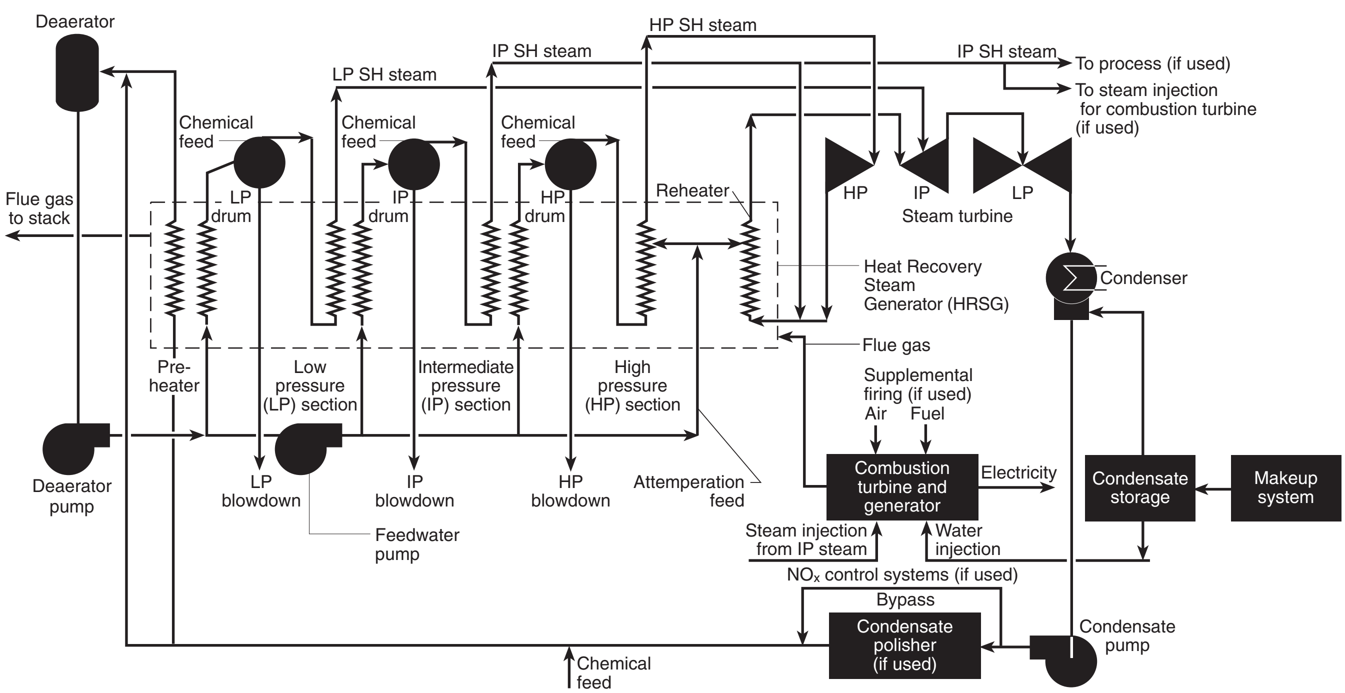
Assessment of the Need to Chemical Clean

Effects of Waterside Deposits on Heat Recovery Steam Generator (HRSG) Performance

Technical Report



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PRODUCT DESCRIPTION

Operational chemical cleaning criteria for heat recovery steam generators (HRSG) are currently based on those applicable to conventional radiant boilers. However, the design and operating conditions in HRSG differ considerably from those of conventional boilers. Thus there is a need to evaluate whether the current criteria for operational cleans are suitable and to consider if alternative and/or supplemental criteria are applicable.

A potentially significant issue with regard to the need for chemical cleaning of HRSG is the impact of internal oxides/deposits on heat transfer rates, unit efficiency, and other thermal performance related parameters. The overall purpose of this project was to conduct some preliminary assessments intended to evaluate the effects of waterside deposits on the operation and performance of HRSG. Results of these assessment activities were in turn utilized in order to consider the possible need for, and benefits of developing operational chemical cleaning criteria for HRSG that are based on changes in performance attributable to accumulation of waterside deposits in the evaporator and economizer circuits over time.

Results & Findings

Initial investigations indicate that HRSG performance degradation is possible as the assumed fouling factor for waterside surfaces in the high-pressure evaporator increases due to accumulation of waterside deposits. These effects may be exacerbated if deposition on the high-pressure economizer is also occurring. Reduction of the economizer approach to saturation temperature is the most sensitive parameter in both triple and double pressure HRSG. As the approach margin or pinch point becomes smaller, the probability of steaming within the economizer circuit increases. In the case of double pressure HRSG subject to deposition in both the high pressure economizer and high pressure evaporator circuits, reduction in steaming capacity and increased stack gas temperatures could also develop as levels of accumulation of operational deposits increase over time. Associated steaming capacity reductions could limit power generation in the steam turbine and, in the case of cogeneration facilities, could impact the ability of the unit to meet steam host demands.

Challenges & Objectives

Combined cycle unit operations require high levels of HRSG performance and dependability. The potential impacts of operational waterside deposits on HRSG availability and reliability now appear to fall into two areas: underdeposit corrosion damage, already observed in working units, and possible performance deterioration, as considered in this work. These impacts and their associated costs must be weighed against the costs associated with those of tube sampling and the planning and performance of operational chemical cleans.

Applications, Values & Use

Assessment findings indicate that the impact of deposits on HRSG performance could be significant and suggest some performance parameters that are most likely to be influenced and thus deserve the attention of plant operators. Deterioration of performance parameters identified by this work could be an indication that deposit levels are increasing and that cleaning is needed to remove the deposits and reverse performance losses. However, additional work is needed to validate and refine the initial findings. Included here are efforts to expand and refine the analysis methodology, monitor trends in performance in working HRSG, and correlate these trends with predictions and results of tube sample analysis.

EPRI Perspective

In 2003, EPRI published *Heat Recovery Steam Generator (HRSG) Chemical Cleaning Guidelines* (EPRI report 1004499), a comprehensive discussion of available information pertaining to the subject. Only interim guidance was provided on operational cleans because very few had been needed or performed on HRSG. Initial criteria for determination of when to clean were based on the experience of conventional fossil units.

This assessment of the effects of deposits on HRSG performance is an important step toward development of cleaning criteria suitable for HRSG. Future Guidelines will consider these aspects as well as experience with underdeposit corrosion damage and failures. This information will be used in establishment of better criteria, tools, and techniques applicable to HRSG.

Approach

The project team used commercial heat transfer design routines to study the effect of high-pressure evaporator tube deposits on HRSG performance. The team evaluated three operating modes:

- Full Load/Unfired – Gas turbine is operating at full load or capacity without the use of duct burners. Exhaust gas flow and temperature dictate feedwater and steam flow rates.
- Full Load/Fired – Gas turbine is operating at full capacity with supplemental duct burners firing also at full capacity.
- 50% Load/Unfired – Gas turbine is operating at 50% capacity without duct burners firing. The feedwater flow is reduced in this case but not by as much as 50%.

Assessments covered horizontal gas path HRSG of triple pressure and double pressure drum type design under new (nominal fouling) and various operational conditions (with increased fouling factors assumed). The team also considered possible implications for other HRSG designs.

Keywords

Heat Recovery Steam Generator
HRSG
Performance
Chemical Cleaning

ABSTRACT

Chemical cleaning criteria for heat recovery steam generators (HRSG) are currently based on those established for conventional radiant boilers. Operational cleaning of conventional boilers is most generally done as needed for prevention or correction of damage and failures due to underdeposit corrosion mechanisms since waterside deposits are known to be a root cause of these mechanisms. Comparable damage by underdeposit corrosion has been experienced in the high pressure evaporator circuits of HRSG.

Inasmuch as the design and operating conditions in HRSG differ considerably from those in conventional boilers, there is an apparent need to evaluate whether the current criteria for operational cleanings are reasonably applicable to HRSG and to consider if alternative and/or supplemental criteria are required. A potentially significant issue with regard to the need for chemical cleaning of HRSG that has not been satisfactorily addressed to date is the impact of internal oxides/deposits on heat transfer rates, unit efficiency, and other thermal performance related parameters.

The overall purpose of this project was to conduct some preliminary assessments designed to evaluate the effect of deposits on the operation and performance of a common HRSG design configurations. This work considered specific HRSG design and operating conditions under varying levels of deposits and levels of waterside fouling on high pressure evaporator and economizer surfaces. This activity confirmed field observations that overheating damage of water touched tubing and tube fins due to buildup of operational deposits is very unlikely. However, the assessments did identify some HRSG operating parameters that are likely to be affected by deposits. The parameter most likely to be affected is economizer approach to saturation temperature. The assessment findings suggest that operational deposit levels could at some point allow steaming within the high pressure economizer circuit. Other parameters could be affected depending on the HRSG design, operating conditions and deposit levels.

Results of these assessment activities were considered with respect to the possible need for, and benefits of developing operational chemical cleaning criteria unique to HRSG that are based on changes in performance attributable to accumulation of waterside deposits in the evaporator and economizer circuits over time.

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1 INTRODUCTION

Chemical cleaning criteria for heat recovery steam generators (HRSG) are currently based on those established for conventional "fired" boilers. Inasmuch as the design and operating conditions in HRSG differ considerably from conventional boilers, there is a need to evaluate whether the current criteria for operational cleanings are reasonably applicable to HRSG or if alternative and/or supplemental criteria should be formulated.

Deposits on heat transfer surfaces of the evaporating section must be periodically removed to minimize the potential for loss in availability and reliability as well as capacity and efficiency losses. Historically, the criteria for chemically cleaning HRSG have evolved based on chemical cleaning guidelines used for conventional units. There are, however, design and operating differences in HRSG as compared to conventional units that can either increase or decrease susceptibility to chemistry and deposit related damage. The lower peak temperatures in HRSG and the lack of extensive preboiler heat exchange surface would be expected to result in a reduced corrosion product deposition rate during steady state operation. (A possible exception to this is combined cycle units with air cooled condensers, although these designs are sometimes equipped with a condensate filter or polisher that may be used at least for startup purposes). There is also a lower probability for overheating failures. However experience has shown that HRSG are susceptible to underdeposit corrosion (including acid phosphate corrosion, hydrogen damage and caustic gouging) in high pressure (HP) evaporator tubing similar to that encountered in waterwalls tubes of conventional boilers.

The more significant issue, therefore, with regard to the need for chemical cleaning that has not been satisfactorily addressed to date for HRSG is the impact of internal oxides/deposits on heat transfer rates, unit efficiency, and other thermal performance related parameters. Internal and external deposits affect heat transfer and thus could affect efficiency/capacity in any fossil steam generator. However, in conventional units, due to the much larger temperature differences between the gas and water/steam sides, deposits are much more critical in terms of unit availability. In other words, excessive deposits will cause tube damage and failures before there is a chance to affect efficiency and/or capacity. In most HRSG, the internal deposit thickness can be quite extreme but will not cause overheating type tube failures. Therefore, the impacts of deposits on HRSG efficiency, capacity, and underdeposit corrosion damage mechanisms become the key aspects of how HRSG deposits influence the need to clean.

The purpose of this study was to evaluate the effect of deposits on the operation and performance of an HRSG in order to determine the factor or factors which could influence the need for an operational chemical cleaning. The impact of deposits was evaluated with respect to their detriment on heat transfer and thus related HRSG performance parameters.

2 IMPACT OF TUBE DEPOSITS ON HRSG PERFORMANCE

A series of technical evaluations was performed to evaluate effects of waterside deposits on heat transfer in HRSG and resultant impacts on performance and develop a possible rationale for establishing cleaning criteria that are based on HRSG-specific performance issues. Commercial HRSG performance design codes for performing heat absorption calculations were utilized for this evaluation. These design codes incorporate an internal fouling factor in the calculation of heat absorption. Internally fouled surfaces will absorb less heat than clean surfaces. However, this effect is somewhat mitigated by the staged nature of the heat absorption process within the HRSG. Reduced heat absorption in one section of the HRSG will result in increased heat absorption in the following section, this due to increased temperature differential effects. Ultimately, however, deposition will affect the performance characteristics of the HRSG and the overall cycle.

It is recognized that the impact of deposits on heat transfer rates is dependent on deposit morphologies under boiling and non-boiling conditions. In order to relate a resistance factor to a deposit accumulation needed for initial determination of chemical cleaning criteria, the density and thermal conductivity of typical deposits in a boiling regime need to be estimated. In this regard, many references from the published literature as well as Alstom Power laboratory tube deposit analytical data were reviewed.

2.1 Thermal Conductivity and Deposit Density

Measured or apparent thermal conductance across steam generator deposits depends on a number of factors. These include deposit chemical composition, porosity (as reflected through the measured density), and structure. The materials of construction in a typical combined cycle are predominantly and often entirely ferritic and stainless steels. One possible exception is condenser tubing which may be fabricated from titanium. Copper alloys are generally not used although, in cogeneration applications, some process equipment in contact with process steam and/or condensate returned to the host may contain copper. The deposits in HRSG are therefore primarily composed of iron oxides (magnetite and hematite). These deposits are similar to those found in tubes drum type utility boilers. Oxide deposits typically exhibit two layers. The inner layer is tightly adherent to the metal surface and uniform. The outer layer is much thicker and more porous. The thermal conductivity of the deposit is primarily controlled by the outer layer.[1,2] In Reference 2, the deposit density and porosity were reported as follows: Density; 3.5-4.6 g/cm^3 (inner), 1.9-2.6 g/cm^3 (outer); Porosity - 12-36% (inner), 52-63% (outer).[2] It should be noted however that experimenters when determining or calculating the thermal conductivity from the thermal resistance of the deposit consider the deposit total thickness.

In the tubing of HRSG evaporator circuits, heat transfer from the internal tube surface through the layers of a deposit is postulated to occur by thermal conduction and latent heat of vaporization for a porous deposit. The thermal conductivity of a thin layer of magnetite decreases linearly with an increase in porosity.[1] The theoretical density of magnetite at zero porosity is reported at 5.2 g/cm.[3] Experiments have shown that the heat of vaporization of water within porous deposits is a much more effective heat transfer mechanism than thermal conduction within the material comprising the structure of the deposit.[1] However, the evaporative effect depends on the deposit porosity and pore sizes. The number and size of the pores determine whether the vapor flows away from the deposit (large steam chimneys) or remains as stagnant vapor. The later severely impedes heat transfer and thus the reason for the lower thermal conductivity as the porosity of the deposit increases. This relationship has been studied by Russian researchers[2-6] focusing mostly in supercritical boilers and to a lesser extent on drum boilers[4,5] during the 1970's and 1980's. These references also cite works by other investigators and report calculated thermal conductivities for various deposit porosities as follows: 1.24 W/mK (0.73 Btu/hr ft °F) at near zero porosity to 0.6 W/mK (0.36 Btu/hr ft °F) at 70% porosity. Another reports a thermal conductivity of 3.8 W/mK (2.25 Btu/hr ft °F) at 27°C (81°F) for natural magnetite. In Reference 3, Mikk reports on experimental thermal conductivity data from 50-500°C (122 - 932°F) on sintered magnetite and hematite (8-10% porosity).[3] The magnetite thermal conductivity at 350°C (662°F) is approximately 2 W/mK (1.18 Btu/hr ft °F). Additional work performed by Mikk with boiler internal deposits (Reference 4) indicates that iron oxide deposits are double-layered; the porosity of inner layer was 10-40% and porosity of outer layer was 30-80%.[4] The thermal conductivity ranged from 0.8 to 1.4 W/mK (0.47 to 0.83 Btu/hr ft °F) in the temperature range from 313 to 386°C (595 to 727°F). In Reference 6, Glebov reports the following that the outer deposit layer controls the thermal resistance.[6] Experimental and calculated thermal conductivities for tube deposits in supercritical steam generators are in the range of 0.45 to 1.0 W/mK (0.27 to 0.6 Btu/hr ft °F).

A report presented at an EPRI/Eskom/VGB conference by Henriksen[7] presents a plot of thermal conductivity data from various sources. The values ranged from 0.5 to 1.5 W/mK (0.3 to 0.89 Btu/hr ft °F) at 15% porosity and 0.2 to 0.5 W/mK (0.12 to 0.3) Btu/hr ft °F) at 80% porosity. Porosity of magnetite found on superheater tubes is 10 to 20%. Porosity of deposited oxide is 65 to 75%. Where the deposit contains large pores that behave as "chimneys", the thermal conductivity is greatly increased. In rare cases as reported by Cohen[8], the boiling heat transfer through an iron oxide thin deposit increased substantially, inferring a negative resistance.

The body of available information clearly indicates substantial and in some cases unpredictable variances in deposit characteristics and thermal conductivity values. Differences depend largely on location in the steam generator and the operating service conditions; for example drum type boilers represent a boiling regime while once through designs are a non-boiling regime. In order to establish suitable thermal conductivity and deposit density values for this work, the data presented in References 9 and 10[9,10] as well as Alstom Power laboratory data were utilized; these data were reduced to average values that were assumed during the evaluation activities. Reference 9 reports on an experimental study on superheater scale thermal conductivity. This scale is primarily indigenous magnetite, formed at high temperatures.[9] It is dense (less porous than typical evaporator tube scale), uniform and tightly adherent. The results reveal a range of values from 1.7 W/mK to 5 W/mK (1.0 to 3.0 Btu/hr ft °F), and the authors recommended that a value of 1.7 W/mK (1.0 Btu/hr ft °F) be used when a conservative assessment of superheater thermal performance is to be performed. The value added to the present evaluation from this referenced study is that it establishes an upper boundary for the thermal conductivity of more porous (and less dense) deposits. As indicated above, the study of deposit characteristics and thermal conductivity in a boiling regime for fossil boilers is limited. However, data provided by Turner et al.[10] from studies on thermal resistance of deposits in nuclear steam generators can be utilized as the deposit morphology is quite similar to that of deposits in fossil boiler tubes. Turner reports that the thermal resistance of porous deposits was measured under both single phase forced convection and flow boiling conditions. Deposits used in the investigation were both synthetically produced and obtained from tubes removed from operating nuclear steam generators. The measured thermal conductivity values under single phase forced convection averaged 1.3 W/mK (0.77 Btu/hr ft °F) and under flow boiling conditions averaged 0.89 W/mK (0.53 Btu/hr ft °F). Other references were listed which provided thermal conductivities of iron oxide (magnetite) deposits under boiling heat transfer conditions: Thermal conductivity ranged from 0.67 to 0.43 W/mK (0.4 to 0.25 Btu/hr ft °F) with corresponding porosity range from 50% to 90%. In cases where the deposit contains large steam chimneys the thermal conductivity was noted to be greatly increased with values ranging from 3.7 to 4.7 W/mK (2.2 to 2.8 Btu/hr ft °F).

Some information on deposit thickness and density was obtained from the Alstom Power laboratory. Tube samples from HRSG evaporators were examined and the scale thickness was measured along with the deposit accumulation. The density typically varied from 1.5 to 3.5 g/cm^3.

The review of this body of information led to the conclusion that the average deposit density and thermal conductivity values under boiling heat transfer conditions could be assumed to be 2.5 g/cm^3 (156 $pounds/ft^3$) and 0.845 W/mK (0.5 Btu/hr ft °F), respectively. The thermal conductivity is valid for temperatures up to 380°C (716°F) and deposit porosity up to 50%. Higher deposit porosities exhibit lower thermal conductivities unless steam chimneys are formed and then the thermal conductivities can increase. The deposit density was further used to correlate deposit accumulation and deposit thickness.

2.2 Heat Transfer Related Parameters

Parameters that could be significantly affected by internal deposits and in turn would provide a measure on the impact on efficiency, capacity, or other damage mechanisms include: HP Economizer saturation approach temperature, HP Evaporator fin temperature, HP evaporator tube temperature, HP steam flow, and stack gas temperatures. The significance and impact of each of these parameters are discussed in the following subsections.

HP Economizer Saturation Approach Temperature

The efficiency of an HRSG is dependent on absorbing as much of the thermal energy from the combustion turbine exhaust gas as practical. Since most of the heat uptake occurs when the water boils, the HRSG is designed with multiple sets of evaporators (and economizers, superheaters, etc.) at different pressures. For example, a triple pressure HRSG is typically designed for pressure levels of approximately 13 MPa (or 1880 psig), 4.1 MPa (600 psig), and 0.7 MPa (100 psig). In addition, the temperature differential pinch point between the gas and the fluid is maintained as small as practical.

After the exhaust gas exits the evaporator area, it enters the corresponding economizer. The gas temperature at this point is above the saturation temperature of the evaporator. Thus if this gas temperature were maintained, boiling would occur in the economizer. Steaming in the economizer can lead to water hammer, vibrations, tube-to-tube temperature differential/expansion, chemical deposition, etc. Therefore, HRSG designers generally strive to achieve a saturation approach temperature (temperature differential between water exiting economizer and saturation temperature) typically in the range of 8°C to 22°C (15°F to 40°F). This range should encompass most of the actual design margins assumed by individual manufacturers.

HP Evaporator Tube Fin Temperature

For a typical HRSG arrangement with superheater and reheater surface upstream of the evaporator, the flue gas temperature entering the evaporator section could be in the range of 480°C to 530°C (896°F to 986°F). The tubes and fins generally are both composed of carbon steel. Fin temperature will rise more quickly than the tube temperature, especially when the tube internal surfaces become fouled. Carbon steel oxidation rate increases rapidly at temperatures above 480°C (896°F). Therefore, if the fins become oxidized, they will deteriorate and lose heat transfer capability.

HP Evaporator Tube Temperature

It's not expected that evaporator tubes will overheat due to internal deposits unless the water flow is substantially reduced. This has been verified in HRSG operating experience to date. In this case, fouling as already discussed will impact other heat transfer surfaces downstream of the HP evaporator in the direction of gas flow.

HP Superheater Steam Flow

Fouling of heat transfer surfaces will have an overall impact on heat absorption and steam generation. This can detrimentally impact the steam turbine output as well as (in the case of cogeneration facilities) steam availability to a process. Essentially the cogeneration plant operator has to make an economic decision of where to send steam when the HRSG cannot meet demand.

HRSG Stack Gas Temperature

Fouling of heat transfer surfaces will affect heat absorption, often resulting in under utilization of available thermal energy. This can result in higher stack gas temperatures and an overall loss in cycle efficiency.

2.3 Heat Transfer Evaluation

Triple Pressure Horizontal Gas Pass HRSG

A triple pressure drum-type HRSG of horizontal gas pass configuration with supplemental duct firing as shown in Figure 2-1 was initially selected for evaluation since this type of HRSG is the most common in newer combined cycle plants. As shown in the figure, duct burners are located between various HP superheater/reheater harp assemblies followed by the HP evaporator. If a selective catalytic reactor is required, this is installed downstream of the HP evaporator since it operates at relatively high gas temperatures. All other heat transfer surfaces are basically located to maximize efficiency as dictated by the difference in temperatures between the water/steam and gas streams. This is exemplified by the placement of multiple HP economizer sections in the gas pass.

Alstom Power heat transfer design routines were utilized to study the effect of HP evaporator tube deposits on HRSG operational parameters. Three operating modes were evaluated: Full load/Unfired, Full Load/Fired, 50% Load/Unfired. These are defined as follows:

- Full Load/Unfired – Gas turbine is operating at full load or capacity without the use of duct burners. Exhaust gas flow and temperature dictate feedwater and steam flow rates.
- Full Load/Fired – Gas turbine is operating at full capacity with supplemental duct burners firing also at full capacity.
- 50% Load/Unfired – Gas turbine is operating at 50% capacity without duct burners firing. The feedwater flow is reduced in this case but not by as much as 50%.

The baseline parameters are calculated by using the inside fouling coefficient (resistance) for new tubes. The value utilized is 0.000017 m^2K/W (0.0001 $ft^2\ ^oF$ hr/Btu), which is typical within the boiler and steam generator industry. In order to optimize the calculation time, the set of resistance input values that needed to be analyzed for determining the effect of deposits, was estimated by calculating typical deposit thicknesses and resistances that would increase the tube metal temperature to 454°C (849^{o}F) in a utility drum boiler. The resistance for a utility boiler was calculated to be about five times the base resistance. Realizing, however, that the heat fluxes and gas temperatures are much higher in a conventional direct-fired boiler, the set of resistances chosen for the evaluation of effects on HRSG performance were at least ten times higher.

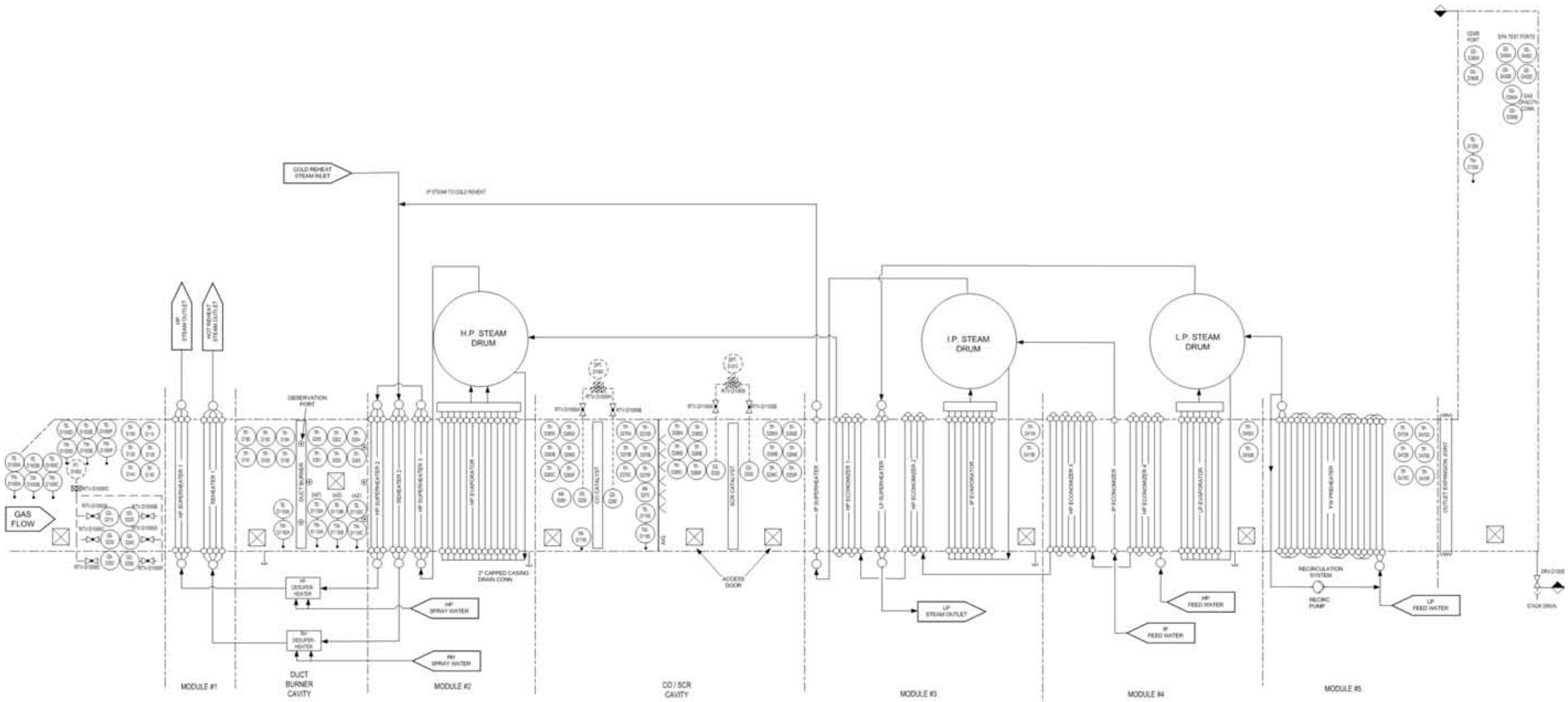

Figure 2-1
Typical Layout of a Triple Pressure HRSG

Data resulting from the initial assessment effort are reported in Tables 2-1 through 2-3. (It should be mentioned that calculations were in made in US units and conversions were made to SI units during preparation of this report. This process involved some rounding of temperature values reported in Tables 2-1 to 2-4.) The parameter most significantly affected under various heat transfer internal resistance values was the economizer approach to saturation temperature for the full load/unfired case (Table 2-1). These data are plotted in Figure 2-2. The approach to saturation temperature decreases as the internal coefficient or degree of fouling increases. This pinch point temperature decreases below the design range as the internal coefficient approaches 0.000171 m^2K/W (0.001 ft^2 °F hr/Btu), which is ten times the base design value for new tubing. The calculated temperature corresponding to this internal coefficient value is between 6°C and 7°C (11 and 13 °F). The temperature value of 6°C (11 °F) was used for the rest of the evaluation activity as the assumed limit for the allowable degree of fouling in the HP evaporator.

Table 2-1
Effect of HRSG Deposits on Triple Pressure HRSG at Full Load/Unfired Conditions

HP Evaporator Fouling Coefficient, m^2K/W (ft^2 hr °F/Btu)	HP Steam Flow, kg/s (10^3 lb/hr)	Temperature, °C (°F)					
		Economizer Outlet	Saturation	Approach to Saturation	HP Evaporator Fin (Maximum)	HP Evaporator Tube (Maximum)	Stack Gas
0.0000171 (0.0001)[1]	55 (440)	301 (573)	309 (589)	9 (16)	384 (724)	321 (610)	86 (186)
0.000171 (0.001)[2]	55 (440)	302 (576)	309 (589)	7 (13)	391 (736)	332 (630)	86 (186)
0.000171 (0.001)	55 (440)	303 (577)	309 (589)	6 (12)	391 (736)	332 (630)	86 (186)
0.000342 (0.002)	54 (430)	306 (582)	309 (589)	4 (7)	398 (748)	343 (650)	86 (186)
0.000479 (0.0028)	54 (430)	308 (587)	309 (589)	1 (2)	402 (756)	351 (664)	86 (186)
0.000599 (0.0035)	---	---	---	0	---	---	---

Notes:

1: Assumed design condition for new tubing.

2: This case assumes economizer fouling at 0.5 times evaporator fouling while the other cases assume fouling of evaporator with no economizer fouling.

Table 2-2
Effect of HRSG Deposits on Triple Pressure HRSG at Full Load/Fired Conditions

HP Evaporator Fouling Coefficient, m^2K/W (ft^2 hr °F/Btu)	HP Steam Flow, kg/s (10^3 lb/hr)	Temperature, ºC (ºF)					
		Economizer Outlet	Saturation	Approach to Saturation	HP Evaporator Fin (Maximum)	HP Evaporator Tube (Maximum)	Stack Gas
0.0000171 (0.0001)[1]	76 (604)	308 (587)	332 (630)	24 (43)	427 (800)	345 (653)	77 (171)
0.000171 (0.001)[2]	75 (596)	310 (590)	332 (630)	22 (40)	436 (816)	360 (680)	77 (171)
0.000171 (0.001)	76 (599)	311 (592)	332 (630)	21 (38)	436 (816)	360 (680)	77 (171)
0.000342 (0.002)	75 (594)	314 (597)	332 (630)	18 (33)	443 (830)	374 (705)	77 (171)
0.000479 (0.0028)	74 (590)	317 (602)	332 (630)	16 (28)	449 (840)	383 (722)	77 (171)
0.000599 (0.0035)	74 (586)	319 (606)	332 (630)	13 (24)	453 (847)	391 (735)	77 (171)
0.000684 (0.004)	74 (584)	321 (609)	332 (630)	12 (21)	456 (853)	396 (744)	77 (171)
0.000855 (0.005)	73 (580)	324 (615)	332 (630)	8 (15)	461 (862)	404 (760)	77 (171)
0.001197 (0.007)	72 (572)	330 (626)	332 (630)	2 (4)	469 (877)	419 (787)	77 (171)
0.001368 (0.008)	---	---	---	0	---	---	---

Notes:

1: Assumed design condition for new tubing.

2: This case assumes economizer fouling at 0.5 times evaporator fouling while the other cases assume fouling of evaporator with no economizer fouling.

Table 2-3
Effect of HRSG Deposits on Triple Pressure HRSG at 50% Load/Unfired Conditions

HP Evaporator Fouling Coefficient, m^2K/W (ft^2 hr °F/Btu)	HP Steam Flow, kg/s (10^3 lb/hr)	Temperature, °C (°F)					
		Economizer Outlet	Saturation	Approach to Saturation	HP Evaporator Fin (Maximum)	HP Evaporator Tube (Maximum)	Stack Gas
0.0000171 (0.0001)[1]	51 (328)	288 (551)	296 (564)	7 (13)	361 (682)	307 (585)	73 (163)
0.000171 (0.001)[2]	41 (327)	289 (553)	296 (564)	6 (11)	368 (694)	317 (602)	73 (163)
0.000171 (0.001)	41 (327)	290 (554)	296 (564)	6 (10)	368 (694)	317 (602)	73 (163)
0.000342 (0.002)	41 (327)	292 (557)	296 (564)	4 (7)	374 (705)	327 (620)	73 (163)
0.000479 (0.0028)	41 (327)	293 (560)	296 (564)	2 (4)	378 (713)	333 (632)	73 (163)
0.000599 (0.0035)	41 (327)	295 (564)	296 (564)	1 (1)	382 (720)	339 (642)	73 (163)

Notes:

1: Assumed design condition for new tubing.

2: This case assumes economizer fouling at 0.5 times evaporator fouling while the other cases assume fouling of evaporator with no economizer fouling.

Table 2-4
Effect of HRSG Deposits on Double Pressure HRSG at Full Load/Unfired Conditions

HP Evaporator Fouling Coefficient, m^2K/W (ft^2 hr °F/Btu)	HP Steam Flow, kg/s (10^3 lb/hr)	Temperature, °C (°F)					
		Economizer Outlet	Saturation	Approach to Saturation	HP Evaporator Fin (Maximum)	HP Evaporator Tube (Maximum)	Stack Gas
0.0000171 (0.0001)[1]	35 (277)	277 (531)	287 (548)	9 (17)	357 (660)	307 (585)	118 (244)
0.000171 (0.001)[2]	34 (266)	265 (509)	287 (548)	22(39)	357 (674)	317 (603)	132 (270)
0.000171 (0.001)	35 (276)	279 (534)	287 (548)	8 (14)	356 (673)	317 (602)	118 (245)
0.000342 (0.002)	35 (274)	281 (538)	287 (548)	6 (10)	363 (685)	326 (619)	118 (245)
0.000479 (0.0028)	34 (273)	283 (541)	287 (548)	4 (7)	368 (694)	333 (631)	118 (245)
0.000599 (0.0035)	34 (273)	283 (542)	287 (548)	3 (6)	369 (696)	334 (634)	118 (246)
0.000684 (0.004)	34 (271)	286 (547)	287 (548)	1 (1)	374 (705)	342 (647)	118 (246)

Notes:

1: Assumed design condition for new tubing.

2: This case assumes economizer fouling at 0.5 times evaporator fouling while the other cases assume fouling of evaporator with no economizer fouling.

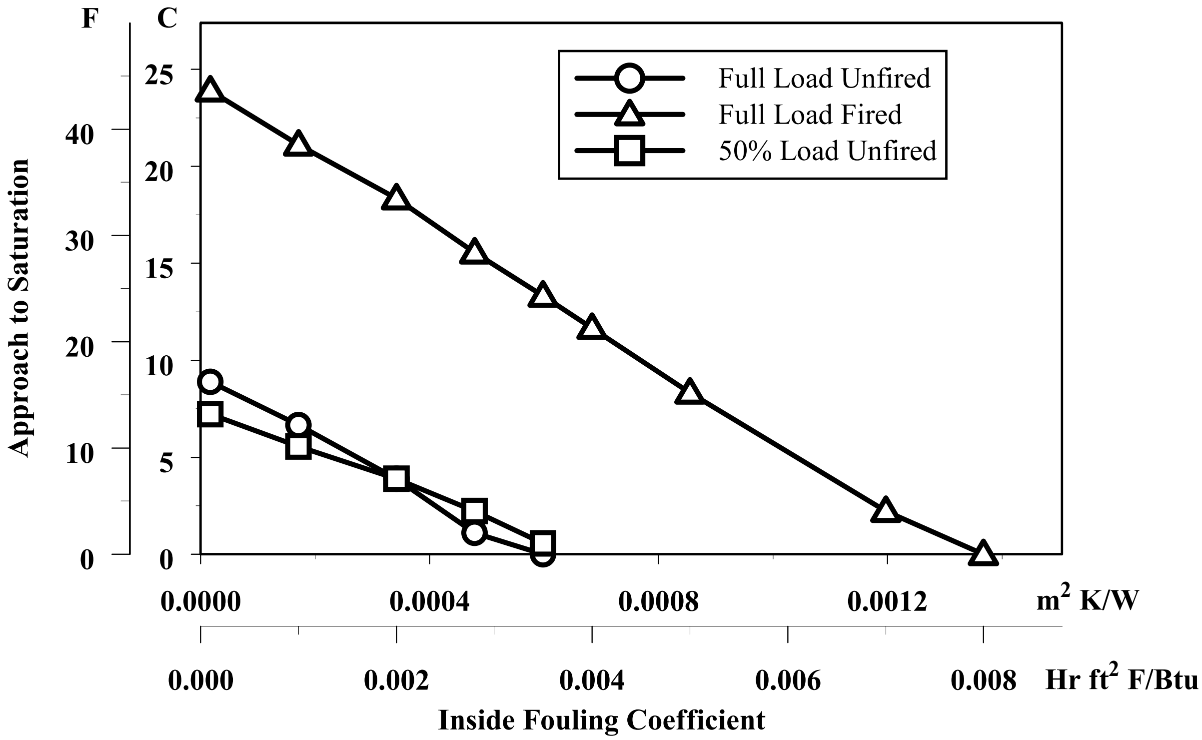

Figure 2-2
Effect of Waterside Fouling Coefficient on the Economizer Approach to Saturation Temperature

Figures 2-3 and 2-4 are plots of two other parameters, fin temperature and steam flow, that were also affected by tube deposits but to a lesser extent. The HP evaporator tube temperatures remained well below the design limit for carbon steel materials. The stack gas temperatures did not change, which was somewhat surprising based on the degree of HP evaporator fouling. As indicated earlier, it was originally anticipated that this parameter would be affected by HP waterside fouling. It clearly demonstrates the capability of components downstream of the HP evaporator in recuperating heat from the exhaust gas and thus maintaining relatively stable stack gas temperatures.

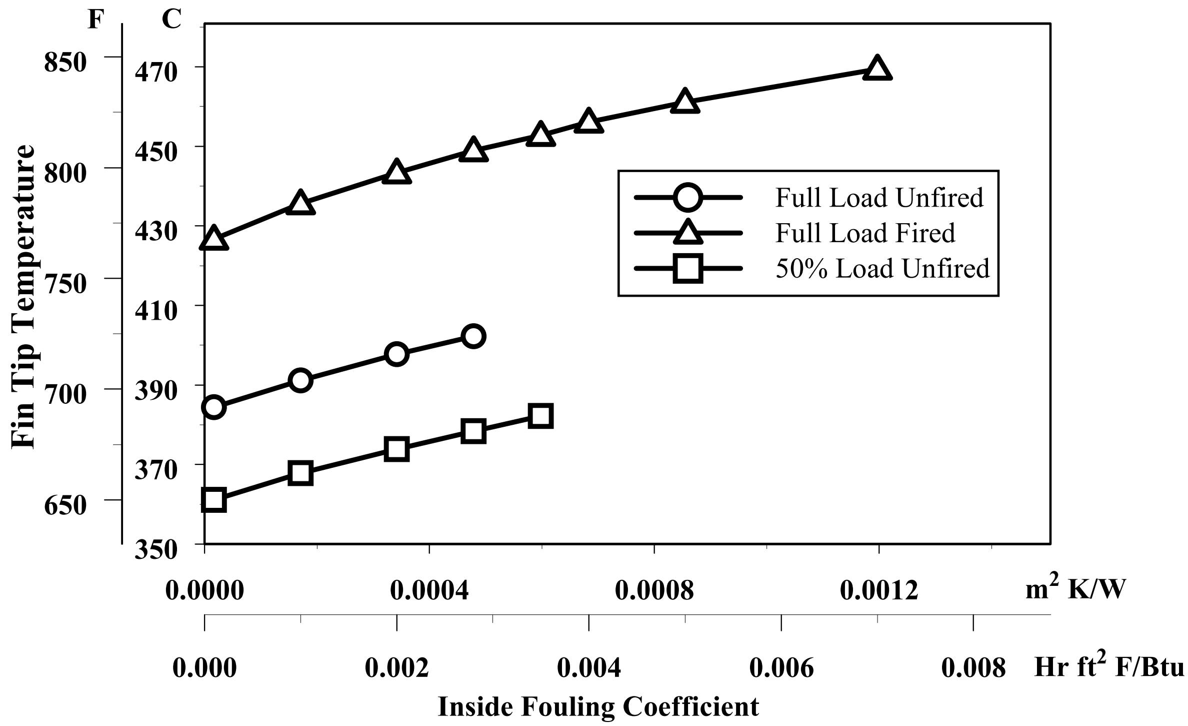

Figure 2-3
Effect of Waterside Fouling Coefficient on Tube Fin Temperature

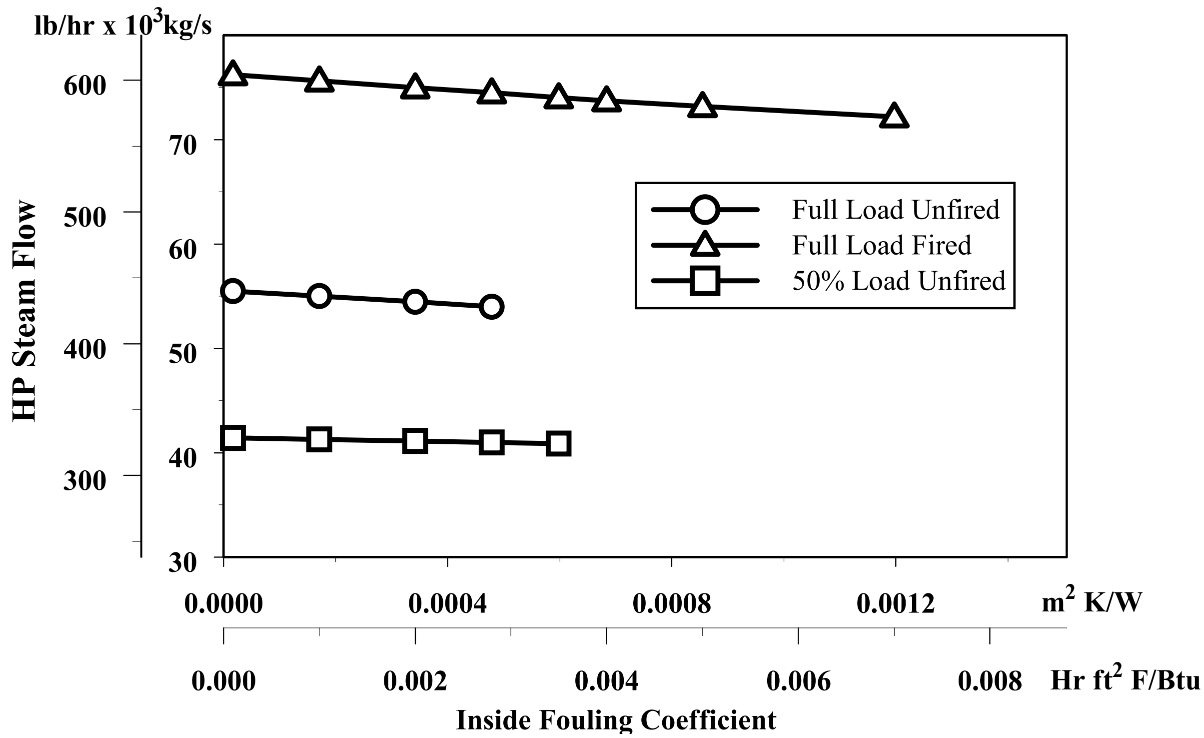

Figure 2-4
Effect of Waterside Fouling Coefficient on HP Steam Flow

As a consequence of the predicted stable behavior of the stack gas temperature, another set of calculations was also performed to observe or trend the impact of deposits on these parameters if the HP economizer tubes were also fouled in addition to the HP evaporator tubes. There is ample experience and information relative to finding deposits in HP economizer tubes especially in units that have experienced flow accelerated corrosion. There have also been cases where the stack gas temperatures have increased with operating time although no correlation was made with fouling of internal surfaces. In this regard, calculations were carried out for the HP evaporator tubing resistance of 0.000171 m^2K/W (0.001 ft^2 °F hr/Btu) that corresponds to 6°C (11 °F) economizer saturation approach temperature. The economizer tube surfaces were assigned half the deposit loading as the evaporator tubes thus the resistance is 0.000085 m^2K/W (0.0005 ft^2 °F hr/Btu) (this value was arbitrarily chosen for the sole purpose of observing the trend). This set of calculation results is also listed in Tables 2-1 through 2-3. The internal fouling of the economizer had a reverse effect on the approach temperature as it increased slightly (by about 1°C or 1.8 °F). The HP steam flow and other parameters remained practically unchanged.

Fouling of the HP economizer impairs heat transfer into the feedwater whereby the saturation approach temperature will increase. However, even with this extent of fouling, the other downstream components were still able to recuperate the additional heat in the gas such that HP steam flow and stack gas temperature are not significantly affected. Therefore, for a triple pressure HRSG, the economizer saturation approach temperature is clearly the key parameter for determining the need to clean from the standpoint of performance.

Double Pressure Horizontal Gas Pass HRSG

A similar evaluation was conducted on a double pressure HRSG (Figure 2-5) at full load – unfired conditions. Unfired conditions are typical for double pressure HRSG. The main difference from triple pressure HRSG system designs is that the double pressure HRSG is a non-reheat cycle and therefore lacks the intermediate pressure (IP) components. In general, a double pressure HRSG/combined cycle is not as efficient as a triple pressure cycle. A test run was also performed with deposits in the HP economizer at half the thermal resistance of that in the HP evaporator. The entire set of calculation results is listed in Table 2-4.

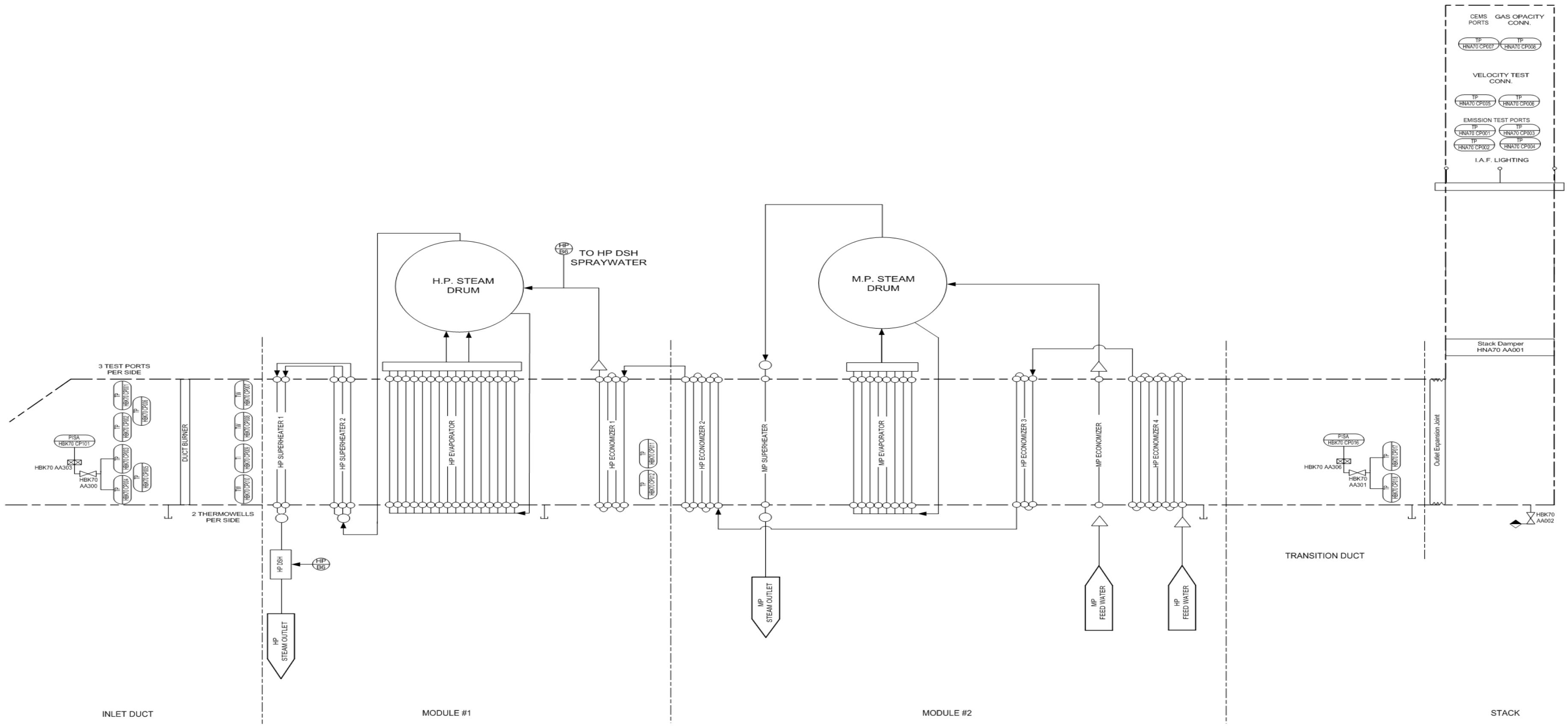

Figure 2-5
Typical Layout of a Double Pressure HRSG

The deposits in the HP evaporator tubes affect the various parameters in a similar fashion as determined for the triple pressure system. As an example, Figure 2-6 is a plot of the economizer approach to saturation temperature. This temperature or pinch point decreases below the recommended range although not as low as in the triple pressure case. However, from a practical point of view, these results can be considered similar. The fouling of the economizer in a double pressure HRSG has a much more significant impact on several of the parameters than noted during assessment of the triple pressure system. This is understandable since there is less heat transfer surface past the HP economizer in the direction of the gas flow. As with the triple pressure case, the calculations were carried out for the HP evaporator tubing resistance of 0.000171 m^2K/W (0.001 ft^2 °F hr/Btu). The economizer tube deposit resistance was assigned half the resistance - 0.000085 m^2K/W (0.0005 ft^2 °F hr/Btu). The internal fouling of the economizer had a reverse effect on the saturation approach temperature as it increased from 8°C to 22°C (15°F to 40°F). The significant impact was on the stack gas temperature as it increased by about 14°C (25°F) (Figure 2-7). The HP steaming rate was also significantly reduced (about 3%) as plotted in Figure 2-8. These last two changes have measurable effect on both the system efficiency and steam turbine output. The other parameters were not significantly affected.

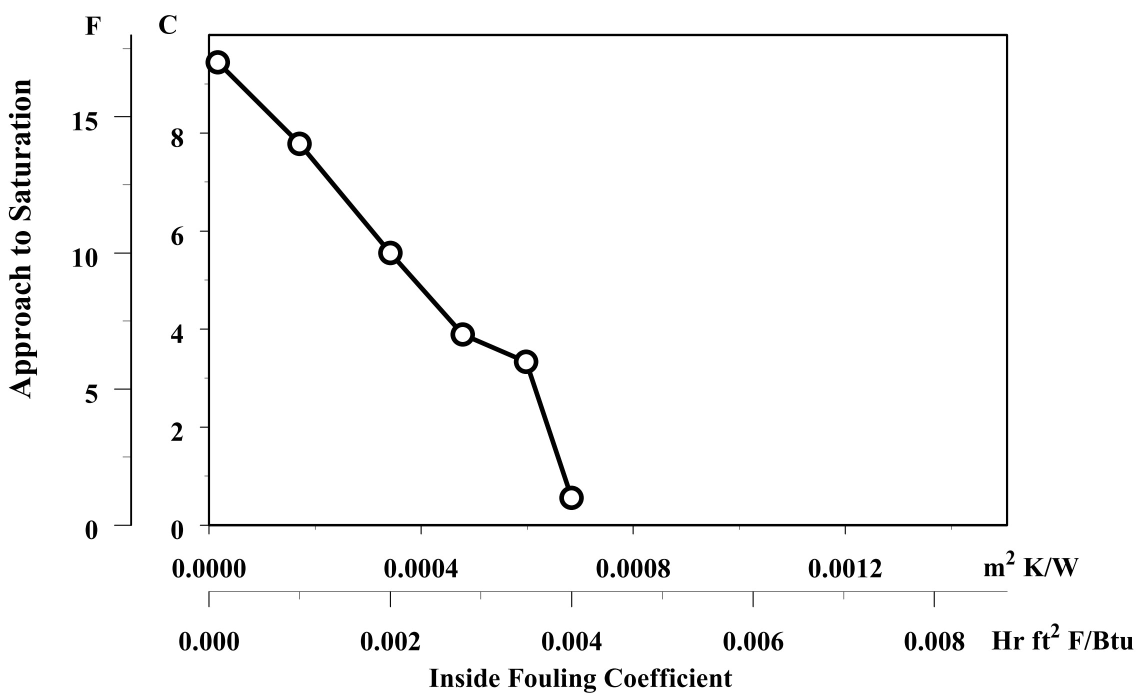

Figure 2-6
Effect of Waterside Fouling on the Economizer Approach to Saturation Temperature in a Double Pressure HRSG

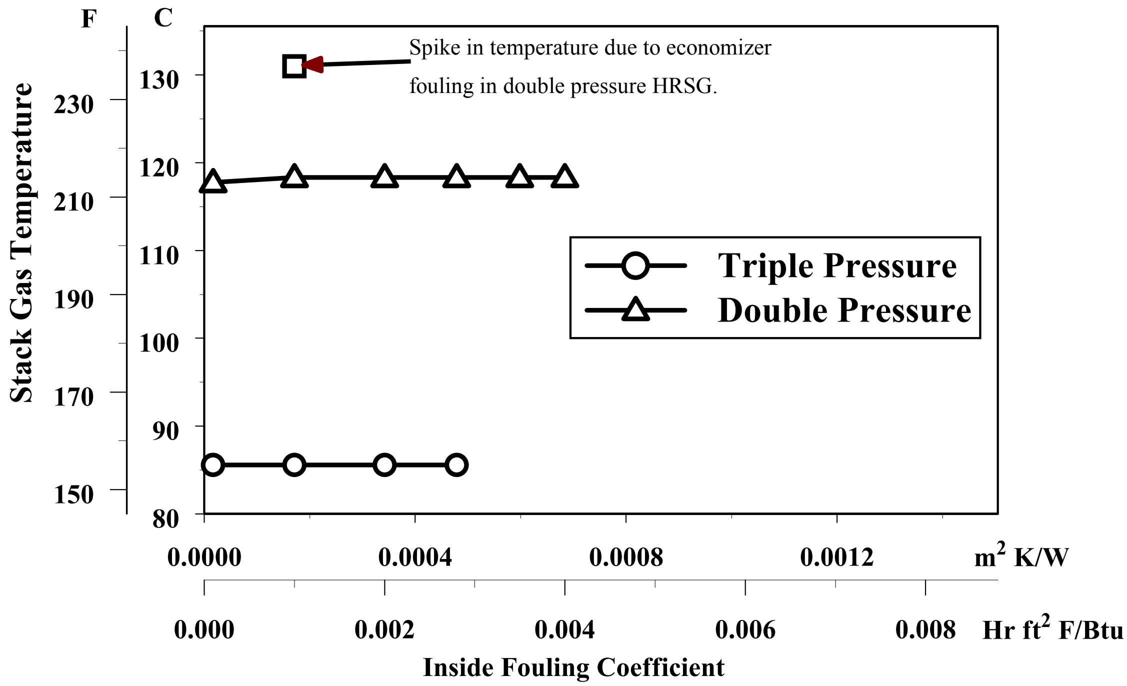

Figure 2-7
Effect of Economizer Waterside Fouling on the Stack Gas Temperature for a Double Pressure HRSG

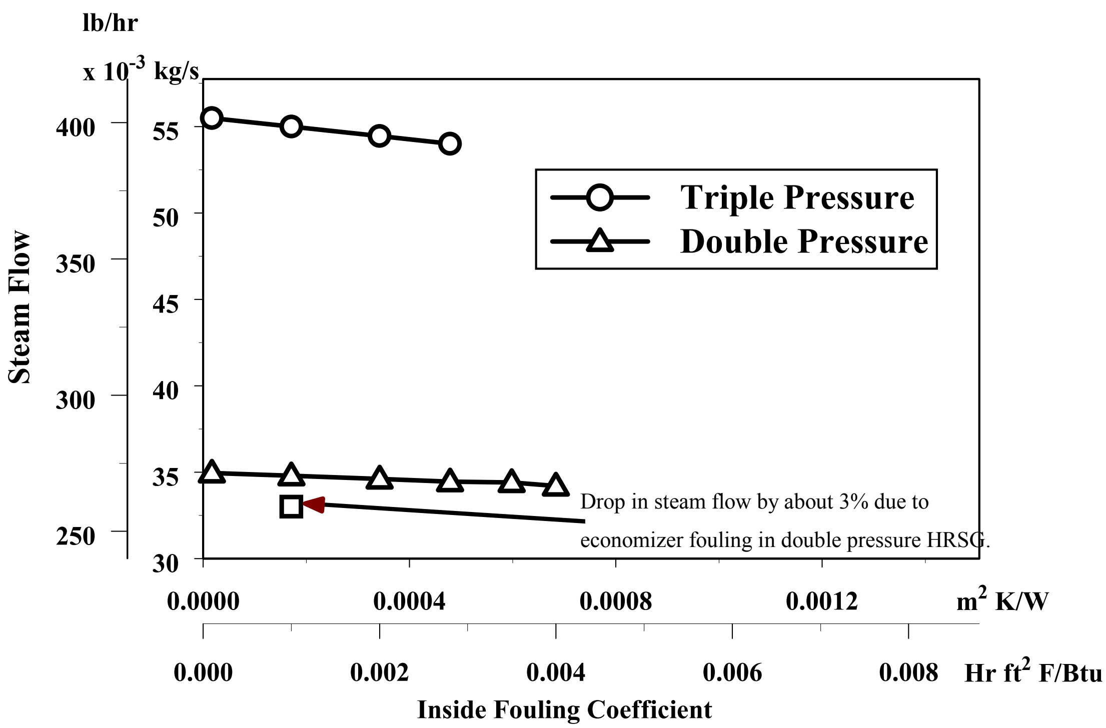

Figure 2-8
Effect of Economizer Waterside Fouling on the Steam Flow in a Double Pressure HRSG

In a double pressure HRSG, fouling of the HP economizer impairs heat transfer into the feedwater whereby the saturation approach temperature will increase significantly. Since the amount of heat transfer surfaces downstream of the economizer is less than in a triple pressure system, there is less opportunity to compensate for the heat loss. This results in a reduction in HP steam flow and an increase in stack gas temperatures. In this case, the key HRSG performance parameters for determining the need to clean become the stack gas temperatures and HP steam flow.

Vertical Gas Pass HRSG

A similar but limited evaluation of a triple pressure HRSG of vertical gas pass configuration was initiated. However, it was quickly realized that, from a systemic point of view, the performance behavior is very similar to the horizontal gas pass HRSG. The systemic-oriented heat transfer program used in these assessments does not distinguish the effect of fouling on individual tubes that may exist due to differences in gas path arrangement.

The deposition level and thus the allowable time interval between operational chemical cleaning of HRSG depends on many operational and water chemistry factors including layup and other equipment protection strategies applied during plant outages. In regards to operational conditions, this evaluation focused on vertical tube surfaces since, as previously indicated, the design code employed analyzes systemic type factors so that a triple pressure vertical tube HRSG behaves similarly to a horizontal tube HRSG. However, it is well established that horizontal surfaces in any steam generator exhibit a higher potential for deposition or the rate of deposit formation both on the bottom of the tube as well as the top of the tube. Under low velocity conditions or when idle, suspended oxides can settle on the bottom of horizontal (or sloped) tubes. Also, under low velocities (such as may be typically associated with low loads), the upper portion of such tubes can experience steam blanketing which can cause localized dry-out of dissolved solids in the steam-water mixture. External (gas side) temperatures are generally low enough that even steam blanketing conditions may not result in overheating of the tube. However, deposit formation is likely to be enhanced by these factors and therefore must be considered in HRSG plants with horizontal tube surfaces.

2.4 Need for HRSG Chemical Cleaning Based on Changes in Performance

For an HRSG, the assessment indicates that HP economizer approach to saturation temperature appears to be the parameter best suited as the key indicator for the need to chemically clean based on performance (and in the absence of tube failures caused by underdeposit corrosion). For the purpose of this assessment, it was decided that when an amount of deposit drove the approach to saturation temperature below 6°C (11°F), it would signal the need for chemical cleaning. This value may not be optimum for all situations though it is considered a useful starting point for the purpose of this evaluation and discussion of the results.

For double pressure HRSG with deposits in the economizer, a decrease in HP steam flow (decreased capacity) and/or an increase in stack temperature could also indicate a need for chemical cleaning. A decrease in steam flow by more than 1% and an increase in stack gas temperatures by several degrees may be justification for a chemical cleaning. These observations however, could warrant further investigation (i.e. economic impact) and results could well indicate that cleaning is required to recover some of these performance losses.

These parameters could be monitored and limits/guidelines provided when cleaning is warranted. However, since these measurements are also influenced by gas-side fouling and other conditions unrelated to deposits, a more positive method to determine the need to clean is required. A tube sampling method is therefore recommended.

Tube sampling is a long recognized practice in determining the need for cleaning a boiler. Guidelines have been established for utility boilers relating tube deposit accumulation to the need for cleaning. Similar guidelines would be appropriate for HRSG. In this regard, a correlation was derived between deposit thickness or accumulation and resistance using a deposit density of 2.5 g/cm^3 (156 pounds/ft^3) and the thermal conductivity of 0.845 W/mK (0.5 Btu/hr ft ^{o}F). This relationship, as determined during the assessment for both the triple and double pressure HRSG systems, is plotted in Figure 2-9. Deposit accumulation or thickness can then be related to the economizer approach to saturation temperature and the other parameters as illustrated in Figure 2-10 for conditions assumed during the assessment.

The subject assessment suggest that the amount of deposit in the HP evaporator tubes that warrants a chemical cleaning based on an economizer saturation approach temperature of 6°C (11^{o}F) (even with a clean economizer) is approximately 40 mg/cm^2 (37 g/ft^2). Interestingly, this amount of deposit corresponds to the amount estimated to provide a thermal resistance in a conventional boiler tube to drive the tube temperature to 454°C (849^{o}F). Further, this amount corresponds to the upper limit of the cleaning guidelines for subcritical boilers when a boiler must be cleaned to avoid overheating problems. If the HP steam flow and/or stack gas temperature in a double pressure HRSG indicate significant changes from normal, then obtaining tube samples from the HP economizer may aid in the determination of the need for cleaning as well as field cleaning requirements.

It is well documented and understood that deposit formation in a conventional radiant boiler is more prevalent in high heat flux areas and associated with higher quality steam-water mixtures. In an HRSG, the heat flux pattern is fairly uniform from bottom to top of the harp assemblies. To date, there has not been sufficient tube sampling to identify a deposit pattern or even preferential locations (though the authors have seen on few occasions just as much deposit in economizer tubes as in evaporator tubes). However, large quantities of deposits (as much as 140 mg/cm^2 or 131 g/ft^2) have been observed in HP evaporator tubes; available results indicate that the distribution of heavy deposits over the waterside surface of samples examined was fairly uniform over the entire circumference. These samples were removed from the upper portion of the harps assemblies (higher quality regions). Therefore, it appears reasonable, in the absence of temperature profile data to obtain tube samples from these upper regions of the harp assemblies. Only the tubes at the periphery of a bundle are accessible. Fortunately, this is not a detriment since heat transfer characteristics don't vary significantly across any one bundle.

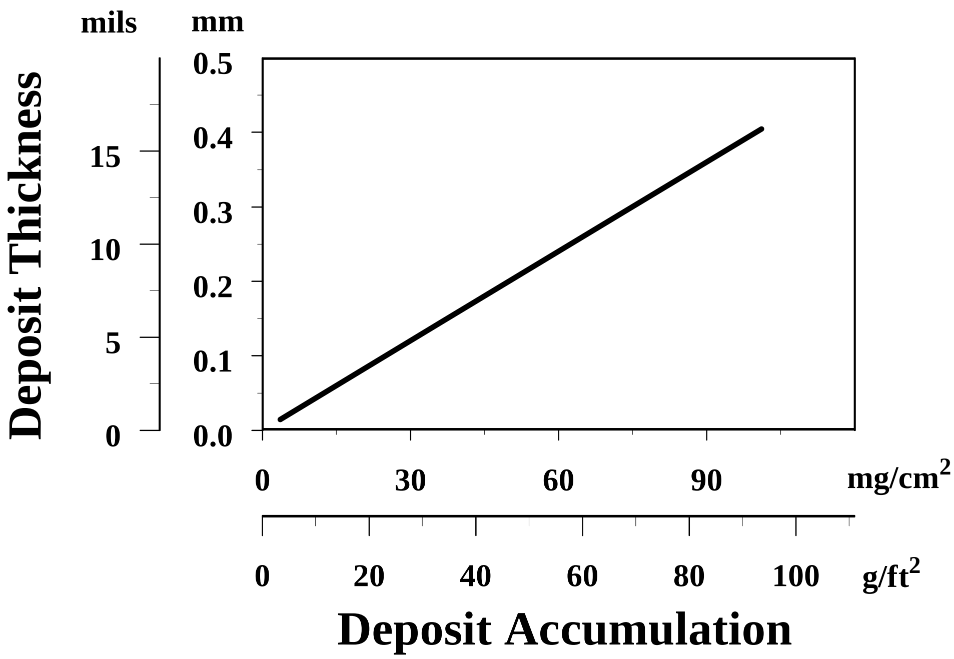

Figure 2-9
Correlation Comparing Waterside Deposit Loading and Corresponding Thickness at a Deposit Density of 2.5 g/cm^3 (156 pounds/ft^3)

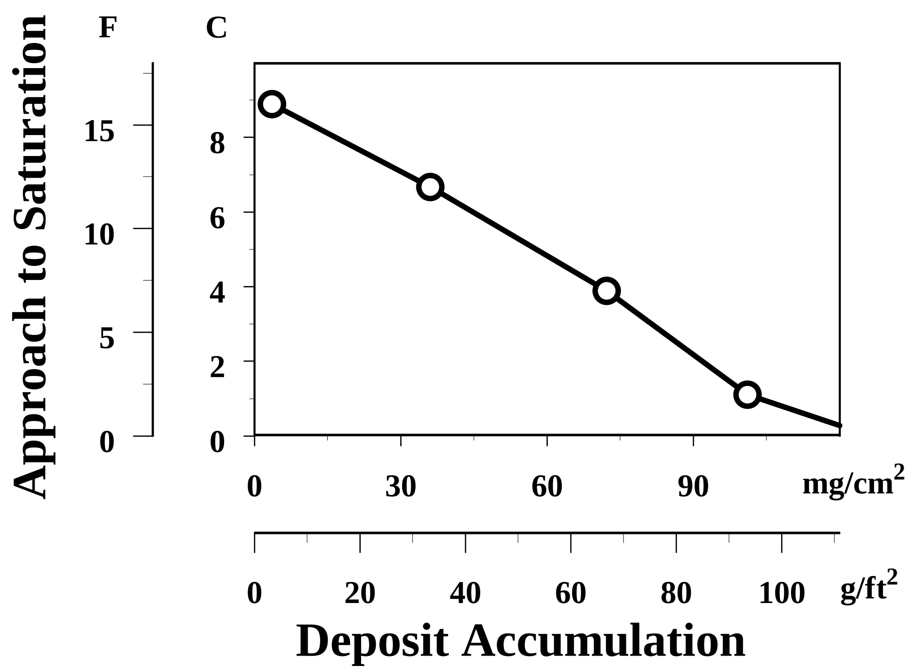

Figure 2-10
Effect of Deposit Accumulation on Economizer Approach to Saturation Temperature

Limited accessibility to these regions and the difficulty in obtaining tube samples is a unique problem with HRSG. For this reason, the frequency of tube sampling will need to be optimized.

Possible approaches to optimization include: (1) HRSG performance trending, (2) chemistry data trending (for possible underdeposit corrosion concerns) and (3) iron transport (which may lead to deterioration in performance or facilitate corrosion damage). However, additional information is needed before useful guidelines applicable to establishment of criteria for tube sampling based on these approaches can be developed.

The first two approaches can be implemented by consideration of data that should be collected during routine service operation of combined cycle units. The third approach is generally suggested as useful during unit commissioning, when troubleshooting possible chemistry problems and when evaluating changes in feedwater chemical treatment. For assessment of tube sampling needs, it could be approached by periodically measuring and trending the concentration of iron oxide in the feedwater. While this can of course be done by grab sampling and analysis, use of integrated corrosion product sampler devices would be the preferred approach. To illustrate the possible use and benefits of this approach, it has been assumed that the iron oxide entering the HRSG with feedwater will completely deposit on heat transfer surfaces. The amount of iron oxide accumulated on HRSG surfaces as for example the HP evaporator can then be estimated by adding the amount of iron oxide entering the system per certain amount of steam production and the amount of iron oxide introduced during a startup. An example of this relationship is plotted in Figure 2-11. This plot is based on the accumulation of iron oxide on the HP evaporator tubes for the triple pressure system and to decrease the economizer saturation approach temperature below 6°C (11 °F). The deposit is assumed to be uniform along the length of the tube and circumferentially. The amount of iron transported to the boiler on a startup following an outage is assumed equivalent to three months of operation under normal design conditions. Actual transport of iron will of course vary and be dependent on outage duration, activities and the equipment protection approaches implemented. It is evident from consideration of this approach as illustrated here that the amount of iron oxide transported to the HRSG after an outage may have a significant impact. This simple assessment clearly emphasizes the importance of maintaining proper layup conditions along with operational water chemistry conditions. A similar procedure and trending approach could be established for double pressure HRSG systems.

The amount of deposit accumulation (40 mg/cm^2 or 37 g/ft^2) that significantly impacts heat transfer parameters in an HRSG is considered fairly excessive for a conventional drum boiler when considering both overheating and corrosion related problems. It is well documented that corrosion attack such as caustic corrosion, hydrogen damage, and acid phosphate corrosion can readily occur in utility drum boilers. In this regard, the pressure conditions in the HP evaporator of a double or triple pressure HRSG are approaching 12.4 MPa (1800 psig) to 13.7 MPa (2000 psig). The tube temperatures and fluid saturation temperatures are certainly high enough to render HRSG HP evaporator tubes susceptible to the same types of corrosion mechanisms as those experienced in conventional boilers. Operating experience in recent triple pressure HRSG has verified that such damage can develop. Therefore, a case can certainly be made that after reaching a certain level of deposit formation, cleaning is required to avoid underdeposit corrosion damage regardless the impact on other parameters.

It would appear, based on these initial assessments, that a deposit accumulation of 40 mg/cm^2 (37 g/ft^2) would represent a reasonable value around which to formulate chemical cleaning criteria in consideration of maintaining HRSG performance. Additional research and field experience is needed to refine this prediction and would be equally desirable to better determine the deposition levels at which the risk of underdeposit corrosion becomes significant. Completion of such work is considered integral to the development of improved cleaning criteria specific to HRSG.

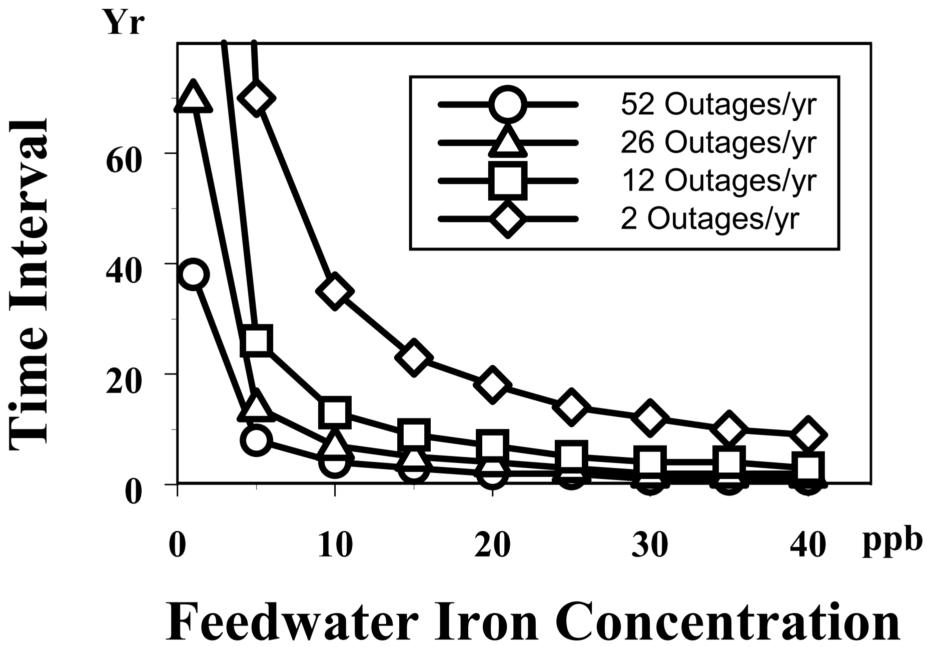

Figure 2-11
Estimate of Time Required for Deposition to Decrease the Economizer Approach to Saturation Temperature to 6°C (11°F)

3
CONCLUSIONS AND RECOMMENDATIONS

3.1 Summary

The purpose of this study was to evaluate the effect of deposits on the operation and performance of an HRSG in order to determine the need for an operational chemical cleaning. It was expected and subsequently confirmed that deposits in the high pressure (HP) evaporator tubes should not result in excessive metal temperatures at which overheating damage will develop. The impact of deposits was evaluated with respect to their detriment on heat transfer and resultant HRSG system performance parameters.

The economizer saturation approach temperature, stack gas temperature, and HP steam flow rate appear in general to represent pertinent indicators of the possible need for chemical cleaning. Based on assessment activities discussed herein, the influence of these factors now appears to be dependent on the HRSG design, where clear differences in the expected behaviors of triple and double pressure designs have been identified. In both a triple and double pressure drum-type HRSG, the most affected parameter is the HP economizer saturation approach temperature. As this temperature differential approaches zero (saturation), steaming in the economizer can occur that can lead to various problems. In addition, fouling of both the HP evaporator and economizer circuits of a double pressure HRSG could lead to loss of efficiency and steaming capacity. Correlation of waterside deposition to HRSG performance indicates that changes in economizer approach to saturation temperature could be used as a criterion useful in determining when collection of tube samples in preparation for possible cleaning is needed.

3.2 Conclusions

It has been confirmed that deposits in the HP evaporator tubes of a drum-type HRSG would not result in excessive metal temperatures and overheating. In both a triple and double pressure drum-type HRSG, the most affected parameter is the HP economizer saturation approach temperature. As this temperature differential approaches zero or saturation, steaming in the economizer can occur that can lead to various problems. The deposit accumulation necessary to approach a minimum temperature differential of around 6°C (11 °F) was about 40 mg/cm^2 (37 g/ft^2).

One set of calculations was conducted to determine the effect of fouling the HP economizer as well as the HP evaporator. The overall impact on the triple pressure HRSG was not significantly different from the clean economizer case. However, in the case of the double pressure HRSG, the assessment predicted an economizer saturation approach temperature increase (indicating less heat pickup), significantly increased stack gas temperature and a significant decrease in the HP steam flow rate. An increase in stack gas temperature implies a decrease in efficiency and a decrease in steam flow will obviously reduce steam turbine capacity.

Based on these initial assessments, the economizer approach to saturation temperature, stack gas temperature, and HP steam flow rate appear to represent pertinent indicators as to the possible need for HRSG chemical cleaning. However, since other conditions such as external tube fouling, etc. will also affect these parameters, it is still advisable to obtain tube samples to confirm that deposits are a significant contributing factor to HRSG performance losses. Tube sampling is also needed to identify specifically which evaporator and economizer circuits should be cleaned.

Assessment findings suggest that deposit criteria could be established to indicate the need for tube sampling as needed to confirm deposits as the cause of HRSG performance losses that could be reduced or eliminated by chemical cleaning. However, further work, possibly including field assessment of HRSG performance and tube cleanliness would be needed to develop useful guidelines. In this assessment, the amount of deposit in the HP evaporator tubes that would warrant a chemical cleaning was estimated at around 40 mg/cm^2 (37 g/ft^2).

It must also be emphasized that this amount of deposit on HP boiling heat transfer surfaces is already at a level more than sufficient to promote typical underdeposit corrosion mechanisms. Existing EPRI Guidelines indicate when cleaning is needed to avoid underdeposit corrosion damage.[11] In the presence or absence of deposit related HRSG performance losses, concerns over corrosion damage should still be recognized as the primary criterion indicating a need to perform operational chemical cleanings.

3.3 Recommendations

It's evident that degree of confidence in the extent of the impact on the various parameters and thus the determination for the need to chemically clean is very much dependent on the assumptions made on the deposit characteristics. The amount of information (laboratory and field) available on deposit density and thermal conductivities is very limited and contained in the references (see Section 4). It is recommended that these characteristics or parameters be the study of future research. The deposits densities could be characterized by examining tube samples from operating units either as these samples become available or by sampling a unit with deposit related problems (under deposit corrosion, stack gas temperature increases, etc.).

The thermal conductivity of actual HRSG deposits would more than likely need to be determined in a laboratory. Laboratory tests can be designed to determine the thermal conductivity of deposits in tube samples obtained from operating units as described in the above paragraph.

Additionally, better understanding is needed with respect to deposit accumulation locations and behavior since as shown the locations of deposits have different impact on system parameters. In this respect, evaluation of tube samples obtained from different locations from units with known problems would help provide this understanding. Deposition modeling is another way to improve the state of knowledge in this area.

This project evaluated drum type HRSG although with only a limited look at the double pressure system. A more in depth evaluation of the various drum-type HRSG systems would be worthwhile especially as a follow up to the earlier proposed studies/research needed to improve on assumptions made during the preliminary assessments. There are also existing and proposed once-through HRSG designs which merit similar study. In addition to system parameters impacted by deposits as observed with the drum type boilers, there are devises such as orifices in once through HRSG which are directly affected by deposits.

4
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