ELECTRIC POWER RESEARCH INSTITUTE

Assessment of Air Preheater Effects on Power Plant Efficiency

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PRODUCT DESCRIPTION

Air Preheaters (APHs) improve overall boiler efficiency by transferring heat from the boiler exhaust gases to the incoming air used for combustion and coal drying. APH performance can have a significant impact on plant efficiency, and therefore fuel consumption, carbon dioxide (CO_2) emissions and power plant economics. This report summarizes the major relationship between APH parameters and heat rate, and presents some preliminary guidelines for evaluating APH upgrades.

Results and Findings

The importance of fuel efficiency and the potential value of CO_2 reductions are the main drivers towards increased awareness of APH performance and its major effect on plant heat rate. This report presents an example that highlights the first-order effects. Other, non-quantified impacts (outage costs, recovered capacity, reduced washes, etc.) are equally important in the overall analysis, and can affect the cost/benefit decision. In the example, by performing an early APH upgrade, the utility recognized a three-year savings of between $3.9M (fuel savings only) and $7.8M (including CO_2) compared to a capital cost of $2.0M, for a simple payback of about 1.5 years for fuel alone, or about eight months if CO_2 is included.

APHs have a very large impact on boiler efficiency. A typical gas temperature reduction of 40Fº (22Cº) across an APH represents about a 1.0% boiler efficiency gain (as long as the temperature reduction is due to heat transfer between the gas and combustion air streams). Given the increasing importance of efficiency due to fuel costs and CO_2 emissions, APH O&M practices must incorporate traditional cost/benefit considerations. It is therefore important for APH operators to consider the overall effect of APH performance in establishing O&M practices and schedules.

Challenges and Objectives

The investigators designed this study to provide the utility industry with guidance on how to evaluate APH performance upgrades with respect to costs, plant efficiency, and maintainability. Traditionally, time- and experience-based schedules and reaction to events (e.g., forced outages) drive APH O&M practices. However, new challenges that emphasize the importance of plant heat rate suggest that utilities should base APH decisions on, or at least consider, the benefits of APH upgrades on plant heat rate.

The major objective of this report is to assess the potential impacts of various air preheater hardware modifications on plant heat rate, and highlight the importance of incorporating these analyses into APH decision-making. The investigators do not intend it to be a discussion of APH technologies. Rather, the report focuses on summarizing the major relationships between APH parameters and heat rate, providing actual data from case studies at several power plants, and presenting some preliminary guidelines on evaluating APH upgrades.

Applications, Values, and Uses

APH performance has recently become even more important due to rapidly increasing fuel prices and the potential need to reduce CO_2 emissions in the power sector. This has made it equally important to understand the options available for APH performance improvement, including the costs and benefits, and boiler heat rate considerations, such that utilities evaluate APH performance on a more global basis. The survey results in this report show that utilities can justify APH O&M upgrades on a condition basis as opposed to a schedule basis.

EPRI Perspective

For many years, EPRI has carried out research on air preheater-related issues, including the impacts of ammonia slip from selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) systems on APH performance. As part of these efforts, EPRI has developed *Air Preheater Fouling Guidelines* (EPRI Report 1004142), published in 2004, and an associated air preheater deposition predictive model. Vendors have developed improved seals, plates, materials, and sootblowing and washing practices to help maintain APH operability and efficiency. Operators have developed O&M procedures (e.g., cleaning cycles and on- and off-line washing) to address these same concerns.

Approach

The project team reviewed recent APH information (literature, vendor websites/contacts), and prepared a survey/questionnaire geared towards utilities to gather information on recent APH upgrades and results. The investigators then analyzed and summarized heat rate impacts from APH operational parameters. The report also provides general guidance on heat-rate-based cost-benefit evaluations.

Keywords

Heat rate
Performance
Fossil plant efficiency
Air preheaters

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1
BACKGROUND AND OBJECTIVES

Background

Air Preheaters (APHs) are devices whose very mission is to improve overall boiler efficiency. This is accomplished by transferring heat from the boiler exhaust gases resulting from combustion to the incoming air to be used for combustion and coal drying. As a result, APH performance can have a significant impact on boiler efficiency and therefore plant heat rate. The heat transfer brought about in the air preheater raises the temperature of the combustion air and lowers that of the flue gas, resulting in improved boiler efficiency. On the other hand, air preheater leakage has a negative impact, increasing both the flue gas flow rate and associated pressure drop losses. All of these represent first-order effects on plant efficiency and therefore on fuel consumption, carbon dioxide (CO_2) emissions and power plant economics.

APHs used in the electric power generation industry are typically of two main types – tubular and regenerative – with the latter being the primary focus of this report. Figure 1-1 provides a general view of a typical regenerative-type APH. Operationally, these devices are relatively simple machines in which a metal matrix of heat transfer plates continually rotates between the hot flue gas and the cold combustion air, transferring energy (heat) between the two. This simplicity, however, does not diminish the importance of proper operating and maintenance (O&M) practices. The massive sizes of APHs dictated by the large surface area required for heat transfer make it essentially impossible to avoid some leakage between the air and gas sides, which tends to increase with time and normal deterioration of seals and rotors. Similarly, the small gas passages adjacent to the thin heat transfer plates, required to maximize the heat transfer area, are conducive to fouling and plugging by ash particles in the flue gas. These issues have challenged stakeholders (vendors, operators, R&D) to develop design and operating approaches to mitigate their negative effects on APH performance.

For many years, EPRI has carried out research on air-preheater-related issues including the impacts of ammonia slip from selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) systems on APH performance. As part of these efforts, EPRI has developed Air Preheater Fouling Guidelines (EPRI Report 1004142), published in 2004, and an associated air preheater deposition predictive model. Vendors have developed improved seals, plates, materials, and sootblowing and washing practices to help maintain APH operability and efficiency. Operators have developed O&M procedures (e.g., cleaning cycles and on- and off-line washing) to address these same concerns.

Figure 1-1
Typical Regenerative APH (courtesy: Howden)

However, APH performance has recently become even more important as a result of rapidly increasing fuel prices and the potential need for CO_2 emission reductions in the power sector. This has made it equally important to understand the options available for air preheater performance improvement, as well as their costs and benefits, such that APH performance considerations are directly linked to their effect on boiler heat rate and therefore evaluated on a more global boiler basis.

Objectives and Approach

This study was designed to provide the utility industry with guidance on how to evaluate APH performance upgrades with respect to costs, plant efficiency, and maintainability. Whereas traditionally, APH O&M practices have been driven by time- and experience-based schedules and reaction to events (e.g., forced outages), the new challenges that emphasize the importance of plant heat rate suggest that APH decisions should be based on, or at least consider, the benefits of APH upgrades on plant heat rate.

The major objective of this report is to assess the potential impacts of various air preheater hardware modifications on plant heat rate, and highlight the importance of incorporating these analyses into APH decision-making. It is not intended to be a discussion of APH technologies. Rather, this report focuses on summarizing the major relationships between APH parameters and heat rate, providing actual data from case studies at several power plants, and presenting some preliminary guidelines on how APH upgrades should be evaluated.

In order to accomplish these objectives, the study involved the following key tasks:

- Review of recent APH information (literature, vendor websites/contacts)
- Preparation of a survey/questionnaire geared towards utilities to gather information on recent APH upgrades and results
- Analyses of heat rate impacts from APH operational parameters

- Preparation of a report summarizing findings

Section 2 provides a summary of the major options for APH modifications and their effect on heat rate, including a general discussion on design and operational considerations. Section 3 summarizes the information gathered from the survey, as well as other case studies from the literature. Section 4 draws some conclusions and provides general guidance on heat-rate-based cost-benefit evaluations.

2
OPTIONS FOR APH PERFORMANCE IMPROVEMENTS

Overview of Design and Operational Considerations

Regenerative APHs have been standard equipment on power plants for six decades. This section is intended to review some of the key design and operational considerations that are relevant to the understanding of APH upgrades in the context of heat rate effects.

Operationally, regenerative APHs are relatively simple devices. Heat from the hot flue gas is transferred to a slow (~1–3 rpm), continuously rotating metal matrix, and subsequently released to the cold incoming combustion air.

In theory, one would want to reduce the flue gas temperature as much as possible to minimize the efficiency penalty due to gas losses. Similarly, it would be desirable to achieve this heat transfer without incurring any pressure loss, thereby avoiding the associated energy loss. These two parameters (gas temperature and pressure loss) represent the major impacts on power plant heat rate attributable to the APH. Increased air temperature is the intent of an APH. If the gas transfers less heat than expected, the resulting air temperature will be lower. Lower air temperatures result in additional work from the pulverizer to dry and grind the coal, as well as additional fuel energy to offset the lower combustion air temperature. Fouling, increased pressure drop, bypassing of inlet air or hot flue gas flow, and dilution with APH air leakage all cause poorer APH and plant performance.

However, in reality, flue gas temperature decisions must consider other operating parameters, including fuel quality and type of equipment downstream. The sulfur content of the fuel and the resulting sulfur trioxide (SO_3) concentration in the flue gas play a major role in determining the appropriate flue gas temperature for a given application. The outlet gas temperature should be above the acid dew point to prevent the formation of sulfuric acid (H_2SO_4) and to avoid all associated problems, such as corrosion and acid-driven deposition. In the same way, APHs must reconcile gas pressure loss, heat transfer effectiveness and space/size requirements. Typically, large electric plant APHs have design pressure drops of about 4-6 inches H_2O. These built-in efficiency losses are unavoidable.

The challenge for operators is, therefore, to be able to maintain these two parameters near design values and not increase them over time. Unfortunately, changes in fuel quality (e.g., sulfur content) and mechanical deterioration of APH components and materials eventually require maintenance and/or upgrades. It is particularly in these areas that full consideration of the cost/benefit tradeoffs, especially the economic value of heat rate improvement and potential CO_2 emissions credits or offsets, can help determine the timing of such repairs or modifications. In other words, by fully considering all the aspects of APH performance effects, APH modifications may be justified in a heat-rate-based cost-benefit analysis, as opposed to the conventional schedule-based approach.

Design Tradeoffs and Operational Constraints

To more easily understand the opportunities and options for improving APH performance, a brief review of the key design tradeoffs and operational constraints is summarized here. Table 2-1 presents a qualitative comparison of ideal APH design criteria and the major real-life constraints or impediments.

Table 2-1
Design Tradeoffs and Operational Constraints

Design Parameter	Objective	Constraint/Impediment	Major Contributors
APH physical size	Minimize	Pressure drop	Unit size, number of APHs
Heat transfer effectiveness	Maximize	Pressure drop	Leakage, fouling, plate material and geometry
APH pressure drop	Minimize	APH size	Leakage, fouling, plate spacing and geometry
Outlet gas temperature	Minimize	Corrosion, acid/ABS fouling	Leakage, fouling
APH leakage	Minimize	Mechanical limitations	Mechanical deterioration, fouling

The tradeoffs shown in Table 2-1 represent the design and operational issues affecting APH performance and provide the basis for what options are available to mitigate deteriorating conditions. Further discussion about each parameter follows below.

- **APH physical size –** The overall size of an APH is dictated by the quantity of the gas/air flows, as well as the inlet and outlet conditions. Mass flow rates are a function of unit size, fuel quality and combustion conditions. The original design of the APH takes into account these factors. Inlet temperature conditions are design inputs and reflect boiler design and operation. Outlet temperatures are discussed below. Cost and real estate considerations normally suggest that the size of APHs should be kept as small as possible. Typical configurations in power plants use two or three APHs per unit due to size and reliability considerations.
- **Heat transfer effectiveness –** APH designers must reconcile more effective heat transfer surfaces (mostly with respect to size of gas path openings, or porosity) with resulting pressure drops and potential for flyash plugging. Heat transfer effectiveness is affected primarily by plate geometry (shape and thickness) and also by its material (e.g., steel vs. alloy vs. enameled coatings).
- **APH pressure drop –** APH design pressure drop represents a compromise between overall APH size, heat transfer plate design (e.g., minimum acceptable opening size for a given coal/ash quality) and balance-of-plant concerns (fan capacities and power requirements). Operating pressure drop will change from the design value over time. APH leakage (increased gas flow) and fouling (increased resistance) are the main culprits affecting operating pressure drop. Leakage mainly affects pressure drop on downstream equipment, such as electrostatic precipitators (ESP), fabric filters (FF), ID fans, and flue gas desulfurization (FGD). Fouling primarily affects APH pressure drop, although because higher APH ΔP increases leakage, fouling also has a secondary effect on downstream equipment. Pressure drop has a direct impact on plant heat rate due to higher fan power

requirements. Ultimately, if system pressure drop exceeds fan capacity, plant load constraints can occur.

- **Outlet gas temperature –** Outlet gas temperature conditions represent a compromise between achieving higher efficiency (lower temperature) and the minimum temperatures compatible with site-specific conditions to avoid low-temperature corrosion and acid deposition. This minimum temperature is affected by the fuel constituents, primarily sulfur content, and incorporates considerations for the cold-end APH baskets (avoid acid corrosion, acid-driven fouling and, more recently, with the use of SCR/SNCR technologies, the formation and deposition of ABS), as well as downstream ducts and other equipment (ESP, FF, and FGD). The gas outlet temperature has a direct impact on boiler efficiency and plant heat rate due to the associated gas (or stack) losses. Gas temperature dilution due to APH air leakage can result in lower than actual readings for gas outlet temperatures and, hence, falsely suggest higher boiler efficiencies. Therefore, gas temperatures must be considered together with APH air-gas leakage (see below) and not as independent values.
- **APH leakage –** Unlike the parameters above, leakage is strictly an unfortunate result of mechanical limitations in regenerative APHs. Figure 2-1 provides a simplified diagram of the major air/gas leakage flow paths in APHs. The limitations are related to three key unavoidable factors: 1) massive size and weight of rotating equipment (i.e., cannot be 100% sealed); 2) wear and tear of metal surfaces (erosion and corrosion); and 3) large temperature differentials as the rotor goes from the cold air side to the hot gas side (thermal distortions). These conditions ensure that some leakage is always present; typical APH guarantees include some level of expected as-new leakage (4-6%). As shown in the figure, leakage minimization is accomplished through the use of seals, whose designs have evolved over the years. Seals are essentially mechanical devices that close the necessary gaps in the APH. These gaps allow for expansion and motion, without which the APH cannot function, but also permit axial, radial and circumferential leakage. Leakage can affect APH performance in two ways: 1) increased gas flows, and 2) decreased heat transfer. The first results in higher pressure losses downstream of the APH, while the latter results in higher gas temperatures and lower air temperatures. As discussed above, both have a harmful impact on plant heat rate. Unfortunately, APH leakage is difficult to measure. Oxygen (O_2) measurements may be misleading, as they may be affected by other leaks (e.g., ducts) as well. Furthermore, it is difficult to discriminate between radial/axial and circumferential (or bypass) leakage, as the bypass leakage paths do not incur a change in O_2 across the air or gas sides and therefore are not accounted for through an O_2 balance test. Different locations of the APH leakage have different effects on APH and unit performance. Cold-end air leakage has no effect on APH performance, but increases total gas flow downstream of the APH (a similar effect as duct leakage has on downstream equipment pressure drop and ID fan performance). Hot-end leakage (similar to boiler casing leakage prior to the APH) reduces the flue gas temperature (through dilution) entering the APH and reduces the combustion air temperature. Lastly, peripheral or bypass leakage, on both air and gas sides, results in lower air and higher gas temperatures.

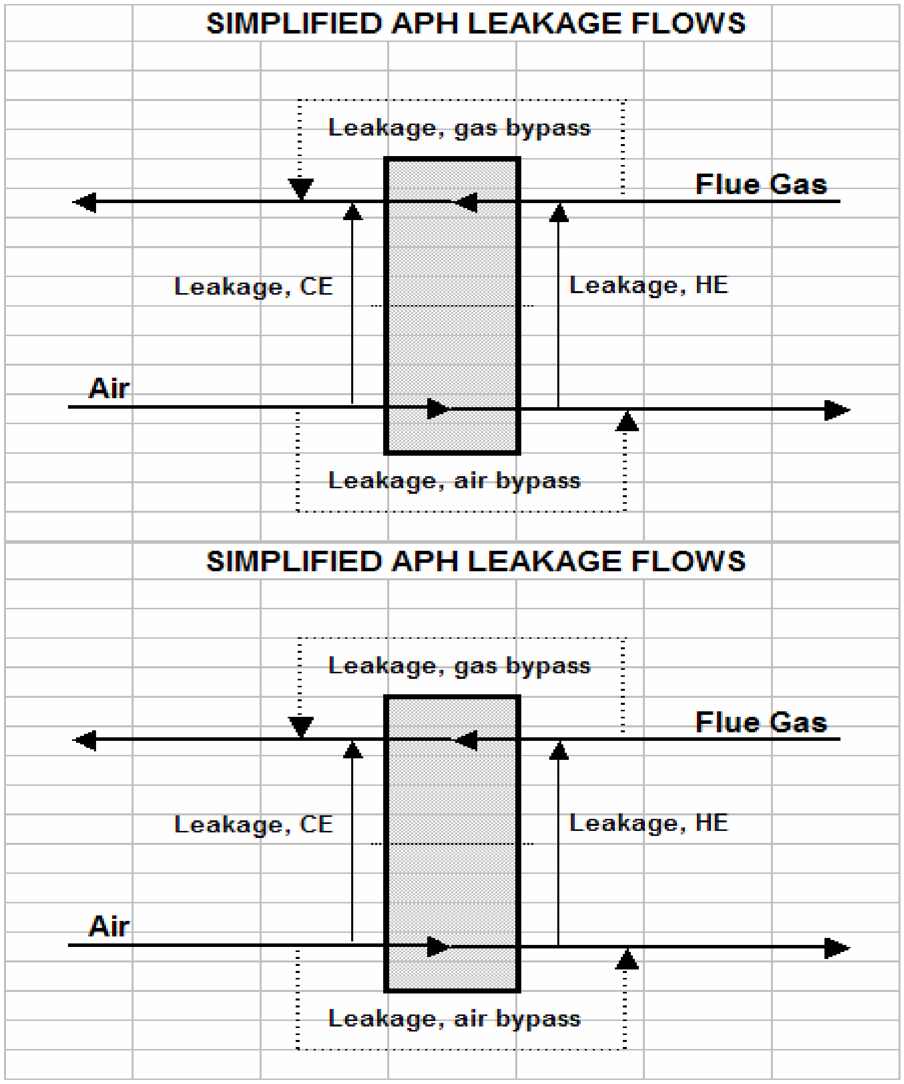

Figure 2-1
APH Leakage Diagram

Options for Improving APH Performance

It is clear from the foregoing that to minimize APH effects on heat rate, one must maintain low pressure loss and low exit gas temperatures, as well as minimal APH leakage. It should be further clear that the key APH parameters affecting pressure loss and gas temperature are leakage and fouling. Therefore, the major options to address APH performance with respect to improving heat rate must address leakage and fouling minimization.

Controlling APH Leakage and Fouling

Referring back to Figure 2-1, it can be deduced that leakage is first and foremost a function of how well the various seals work – the larger the gaps, the higher the leakage. Secondly, leakage is directly related to the pressure differential between the air and gas sides of the APH – the lower this differential, the lower the leakage rate. Therefore, it follows that there are two main approaches to minimizing APH leakage: 1) fixing, upgrading or using better, longer lasting seals; and 2) reducing pressure drop across the APH.

Seal Technology

Seal technology has evolved over the years in response to APH leakage concerns. Axial, radial and circumferential seals and plates are offered by the major OEM vendors, as well as aftermarket companies. A variety of designs and materials are available, and vendors offer their own trade name products. Seal life is dependent on many variables, but typical life-cycle expectancy ranges from two to nine years between replacements, depending on seal technology and operating conditions.

Heat Transfer Baskets/Plates

As stated previously, APH pressure drop is driven by the resistance of the flow channels adjacent to the heating plate elements. This resistance is a function of both the geometry of the heating elements (porosity and surface shape), as well as their fouling condition (cleanliness). Addressing the type and geometry of heating elements requires changing to a plate of different geometry. Obviously, the tradeoff between pressure drop and heat transfer effectiveness (and resulting gas temperature) must be evaluated when changing heating elements. With respect to dirty or fouled plates, more effective cleaning approaches are potentially attractive, but the tradeoff here is to mitigate mechanical/corrosion damage during the cleaning process.

Heating plate elements are typically defined by their geometry and materials. Carbon steel, corrosion-resistant alloys and enameled surfaces are typical in the industry. Similarly, a variety of shapes, well known by their popular denominations (e.g., DU, NF, NU, CU, and DNF) are widely available. These geometries and materials have specific performance characteristics and must be compatible with the particular application, but must also account for the tradeoffs between pressure drop, heat transfer and fouling characteristics.

Fouling Control Options

Cleaning approaches (sootblowing, sonic devices, and washing) have also evolved over the years, and much work has been done to improve plate fouling control. Plate cleanability is affected by the cleaning device, as well as the plate geometry itself. With the more recent concerns about ABS fouling due to SCR/SNCR applications, deeper cold-end plates have been preferred over the conventional shorter cold-end depths, to prevent sootblowing energy from dissipating in the spaces between element layers.

In parallel, improved sootblowing and washing methods have been developed. Steam and air sootblowing, as well as high- and low-pressure washing, are available. Retractable, multi-head and swing/movable sootblower designs are commercially available. The appropriate choice is site- and conditions-specific. APH washes have traditionally been conducted off-line to avoid water-related damage at APH operating temperatures. More recently, approaches have been developed to accomplish APH washing while on-line (typically at reduced loads). Some U.S. utilities have adopted European techniques of varying rotational speed during on-line washing to insure complete cleaning of the outer sections of baskets.

Effects on Boiler Efficiency and Plant Heat Rate

The main APH parameters that impact boiler efficiency are increased pressure loss and gas temperature. As discussed, pressure loss affects fan power (plant parasitic loss), and potentially plant generating capacity, while stack gas temperature affects boiler efficiency (and also potentially fan capacity due to the higher volumetric gas flow at the higher temperature).

These two effects are easy to quantify if the before and after conditions are known. Once quantified, the resulting economic impact can be calculated from the heat rate gains and CO_2 reductions (if and when appropriate).

Power Required for Increased Pressure Drop

- HP = [Flow rate (ACFM) x ΔP (in H_20)] / [(6356) x fan eff (%) x motor eff (%)]
- Equivalent kW = HP x 0.746 (kW/HP)

Efficiency Loss Due to Gas Temperature

- The loss due to the change in APH gas outlet temperature can be calculated for a particular unit based on combustion efficiency calculations. However, the conventional rule-of-thumb of *1% efficiency loss per 40ºF of gas outlet temperature* represents an acceptable correlation for these purposes. Hence,
- Equivalent kW = [(Initial APH gas outlet temperature – new APH gas outlet temperature) x (1% / 40)] x (boiler kW)

Additional analyses are provided in Section 4, including a hypothetical case study.

3 SURVEY SUMMARY

A questionnaire was prepared and submitted to several EPRI member utilities to identify recent APH modifications and the resulting performance improvements. The main objectives of these case studies were (1) to identify, through real life experience, actual results from the undertaken modifications or upgrades; and (2) to document or estimate the effects on heat rate and plant operation. While in many cases detailed testing of the APH alone does not necessarily follow APH maintenance or upgrade work, the survey confirms the general expectations and illustrates the value of the APH upgrade options. Whether detailed performance tests are carried out often depends on the type of contract the utility has with the supplier of the APH upgrades and what other plant modifications/upgrades are implemented at the same time. For example, if APH heat transfer baskets and seals are the only upgrade in the plant, and the contract includes an acceptance test, the effects of the APH upgrades can be easily identified. However, if other plant upgrades are being implemented at the same time, or if operating conditions change significantly, it may be more difficult to isolate the effect on plant heat rate of the APH work.

APH upgrades are typically justified by:

- Deterioration of performance (e.g., seal leakage)
- Improved heat transfer basket designs
- Accommodations for a new fuel
- Accommodations for a new ammonia-based NO_x control system
- Improved cleaning devices to address fouling conditions

These justifications can result in heat rate and/or capacity/reliability improvements where fuel savings and/or increased revenue can be determined and compared to the cost of the upgrade.

Table 3-1 presents a summary of the results from the survey. The main performance results are provided where available. The background for the various modifications is not known in all cases, but a couple of examples illustrate the varying reasons driving the modifications.

In case studies A-1 through A-4 and B-1, major APH retrofits were conducted. These included rotors, posts, diaphragms, basket design changes (bolted vs. welded), layer configuration (three-layer to two-layer), seals, and motors (variable speed). In the following case, the decision was driven by the fact that the original rotors had been in service since the early 1970s. "…. *The rotor posts and diaphragms had numerous cracks repaired during that time and were structurally suspect. The gas inlet temperatures were above the 750 degree design temperature further compromising wheel integrity. The new basket design will allow complete basket replacement in about 3 weeks versus 7 weeks for the original configuration. Also the gas side pressure differential will be reduced from about 9 inches to 5 inches, reducing auxiliary power and minimizing fan related load drops."*

In other words, the major retrofits undertaken in these four case studies went well beyond routine seal replacement or basket design changes. The results therefore cannot be attributed to an individual component but rather to the overall retrofit.

Case study C-1/2 involved lesser modifications. The stated objectives were to "…*reduce air/ gas flow, temperature and DP, and basket deterioration."* In this case the upgrades were conducted over a period of time as follows:

- *"Changed out hot, hot intermediate and cold end layers of baskets in Unit 2 in 2007 and Unit 1 in 2008.*
- *Changed hot end radial seals from 12 gage OEM style to full contact stainless steel seals in Unit 2 in 2004 and Unit 1 in 2005.*
- *Added deflector shields over hot end gas side bypass seals in Unit 2 in 2004 and Unit 1 in 2005.*
- *Doubled the number of axial seals in Unit 2 in 2004 and Unit 1 in 2005."*

The owner used several seal technologies from different vendors as well. This case study represents a more direct before and after comparison of the results of the seal and basket upgrades.

Table 3-1 focuses on information obtained from electric utilities in the US, but it was supplemented by a few cases documented by APH upgrade suppliers. The Howden case studies in the table, as well as several others, are described in their website www.howden.com.

APH HR survey - Summary														
Plant/ Unit	Size (MW)	APH # & type	MODIFICATIONS	% Leakage		Delta P		Exit Gas Temperature		HR Effect (%)		Cost ($)	Source	Comments
				Before	After	Before	After	Before	After	Source	Estimated			
A-1 (US)	623	2-bisector	3 layer to 2 layer conversion; rotor, seals, posts,diaphrams	8	NA	9.2	6.1	325	336	NA	~0%	5.5M	EPRI APH survey	
A-2 (US)	615	2-bisector	same as above	12	3-4.6	9.8	4.3	328	341	NA	~2.5%	5.5M	EPRI APH survey	
A-3 (US)	633	2-bisector	same as above	6.5	NA	6.6	5.1	349	339	NA	~.35%	5.5M	EPRI APH survey	
A-4 (US)	633	2-bisector	same as above	11.5	NA	9.3	5	336	295	NA	~.5%	5.5M	EPRI APH survey	
B-1 (US)	615	2- trisector	3 layer to 2 layer conversion; rotor, seals, gearbox drives	NA	NA	14	5	296	295	NA	~.9%	8M	EPRI APH survey	
C-1/2 (US)	600	2- trisector	changed baskets on H/I/C layers; new seals - radial, axial, bypass	14	8	14	8	NA	-30	1.7%	~1.5%	50K (seals); 2M total	EPRI APH survey	
D-1 (US)	50	1-bisector	Seals	NA	NA	NA	NA	NA	NA	2%	NA	35K	Power Eng./ Paragon	2% reduction in coal; FD fan amp reduction (7%)
D-2 (US)	560	bisector	new frame; new baskets; new seals (radial, axial, bypass)	25	10	NA	NA	355	315	1.60%	~1%	NA	EPRI	
Matra 3 (Hungary)	200	2- bisector	VN sealing	24	7	NA	NA	401	327	1.9%	~1.9%	NA	Howden	
Ince B 5 (UK)	500	2- bisector	VN seals; replaced DU w/ FNC elements	12	6.5	NA	NA	334	307	~0.65%	~0.65%	NA	Howden	Gained 25MW
W. Burton (UK)	500	2 SA; 2PA Bisector	VN seals; doubled # of radial & axial seals	8	4.3	NA	NA	NA	NA	~4%		NA	Howden	Recovered 20MW

Table 3-1
APH Heat Rate Survey: Summary of Results

The following are additional clarifications of the information presented in the table.

- **Plant/Unit** – The plant and/or unit name is provided when from a publically available source. Responses to the survey were kept confidential, and such plants are listed as A-1, A-2.
- **Modifications** –This column indicates the APH retrofits undertaken. In some cases, only one option was implemented (e.g., seals only), whereas in others, multiple modifications were included (e.g., seals, baskets, and major layer configuration changes). It should be noted that the results may reflect the combined effect of multiple changes undertaken.
- **% Leakage** – Where available, the before and after leakage numbers are provided. As discussed in Section 2, leakage affects APH heat transfer and gas flows, both of which impact unit heat rate. Where before and after temperatures are available, the flue gas loss and associated efficiency penalty can be estimated. The other effect of leakage is reflected in higher gas flows, which result in higher pressure drops across downstream equipment (e.g., ducts, ESP, FGD).
- **ΔP** – Where available before and after APH pressure drop values are provided, ΔP values can be directly used to estimate additional fan power requirements. APH pressure drop can impact boiler capacity in situations where fan capacity is exceeded. In two cases (W. Burton

and Ince B) capacity recovery was indicated, although it is not clear whether other boiler work contributed to the final result in the case of Ince B.

- **Gas Temperatures** – This refers specifically to APH gas outlet temperatures, which have a major effect on boiler efficiency losses (~1% per 40ºF). Where available, the impact on HR includes the contribution of this loss from both the source and estimated values.
- **HR Impact** – These columns present the effect on heat rate associated with the APH modifications described and the results shown. Two sub-columns are presented.
  - **Source** – These numbers are presented as obtained or described in the source document or communication. In some cases, they reflect just the HR effect associated with the relevant parameters shown, such as at Matra and Ince B, where the HR effect reflects the gas temperature change due to the modifications. In other cases, the HR effect number reflects the total impact on plant heat rate, which accounts for other plant-equipment-related benefits due to the APH changes (e.g., total fan power reduction or recovered capacity), such as in W. Burton and units C-1, D-1, and D-2.
  - **Estimated** – This column presents the estimated HR effect based on the parameters provided by the original source. Hence, gas temperatures and APH ΔP are used to calculate their impact on heat rate (as shown in Section 2). To reiterate, where leakage values are given, any additional fan power associated with downstream equipment is not included, as we do not have that information. (Note: pressure drop is proportional to the square of the flow rate, meaning a 10% increase in flow should increase pressure drop across a given piece of equipment by 21%. For example, a fabric filter operating at normally 6.0 in H_2O would experience an increase to about 7.2 in H_2O). Where both source and estimated values are the same, it means the original source also used APH ΔP and gas temperatures as the only contributors in their HR results (Matra and Ince B). Conversely, where the two columns differ, the original source used plant performance data beyond these two parameters used in the estimated column.
- **Cost** – The cost numbers presented must be considered very generic, not necessarily because the numbers provided are not accurate, but because in some cases we cannot determine the individual impacts on costs of the many modifications described. For example, the $5.5 million for units A-1 through A-4 and B-1 includes the total project costs which, as described, involved many component upgrades and retrofits. In the cases of C-1 and plant X, the cost of the APH seals retrofit seems to agree quite well ($35K versus $50K).

In summary, the results in Table 3-1 indicate that APH modifications resulting in lower leakage rates, decreased operating pressure drop and reduced gas outlet temperatures have significant impacts on boiler efficiency and plant heat rate. Actual improvement in heat rate will vary not only as a function of the APH before and after performance, but also due to the impacts on balance-of-plant conditions.

4

GUIDANCE ON EVALUATING APH UPGRADES

APHs have a very large impact on boiler efficiency. A typical gas temperature reduction of 400ºF (204ºC) across an APH represents about a 10% boiler efficiency gain (as long as the temperature reduction is due to heat transfer between the gas and combustion air streams). Given the increasing importance of efficiency due to fuel costs and CO_2 emissions, APH O&M practices must incorporate traditional cost/benefit considerations. It is therefore important for APH operators to consider the overall effect of APH performance in establishing O&M practices and schedules.

As discussed in Section 2, the direct impact of APH performance on boiler efficiency or heat rate is easily calculated. The major performance parameters – gas outlet temperature, ΔP and leakage – affect boiler efficiency (gas temperatures) and power consumption (ΔP and leakage). This section provides some general indications of the potential effects due to the more common performance upgrades. It is focused on the three main parameters and typical solutions discussed in Section 2:

- APH leakage – seals
- APH ΔP – element type, cleaning system
- APH heat transfer (gas temperatures) – element type, seals

Major APH modifications – such as rotor, motors, gearboxes, etc. – are not discussed, as their replacement strategies are driven by larger condition-based maintenance considerations, which are beyond the scope of this report. Table 4-1 summarizes the major considerations necessary to properly evaluate the cost/benefit of APH upgrades.

Table 4-1
Major Items to Consider in Cost/Benefit Analyses

COSTS	BENEFITS
• Cost of upgrade components o Capital o Installation • Outage costs o Capacity o Energy o Purchased power	• Heat rate/fuel savings o Reduced APH ΔP o Reduced APH leakage ▪ Reduced ΔP in downstream equipment o Reduced fan power consumption • Reduced maintenance o Fewer outages for APH washes • Recovery of lost capacity o Remove fan limitations

Note: Not all items are applicable to all situations. Site-specific analyses would use only those applicable.

Efficiency Benefits

To reiterate, the main APH parameters that affect plant heat rate are pressure loss, and combustion air and stack gas temperatures. Pressure loss affects fan power (plant parasitic loss), while air/gas temperatures affect boiler efficiency. APH leakage increases gas flow to downstream equipment and results in additional pressure loss across such equipment, requiring additional fan power. These represent the key effects on plant heat rate due to APH performance. Secondary effects are also potentially present, such as gas temperature effects on ESP performance (due to resistivity changes and volume flow rate), which may in some cases require higher TR power settings. (Note that increased gas volume flow rates can also affect the performance of ESPs and fabric filters, resulting in changes in opacity and/or particulate emissions). Again, it must be restated that the constraints discussed in Section 2 need to be taken into account. For example, stack gas temperatures cannot be lowered below a certain level due to corrosion and fouling considerations.

Figures 4-1 to 4-3 present nominal relationships between these APH parameters (gas temperature, APH ΔP and APH leakage) and their effect on heat rate. These effects are additive, and hence can represent a significant source of plant heat rate improvement.

- APH Gas Outlet Temperature – Figure 4-1 shows the nominal effect of decreasing gas temperature on boiler efficiency. For example, a decrease in temperature from 330ºF to 300ºF would result in an equivalent efficiency (or fuel savings) improvement of about 0.75%.

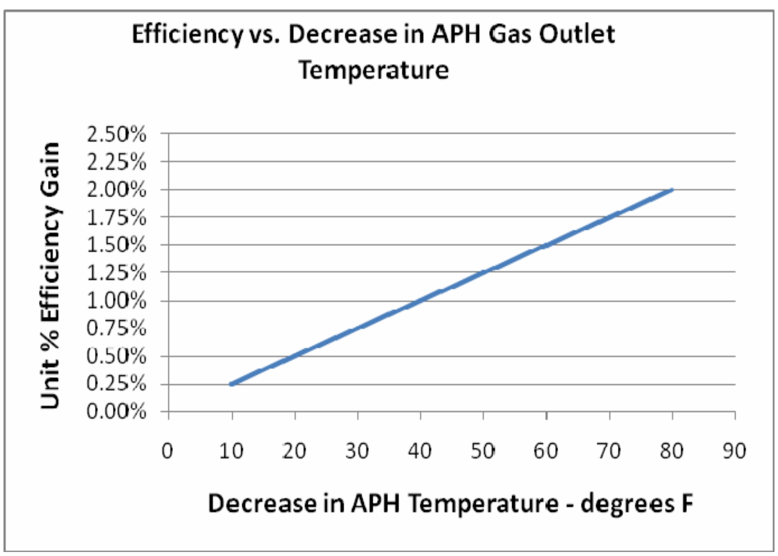

Figure 4-1
Effect of APH Gas Outlet Temperature. Example: Basket Upgrade

- APH Pressure Drop – Figure 4-2 presents the effect of a reduction in APH pressure drop on efficiency. This efficiency gain is attributed to the decrease in fan power requirement.

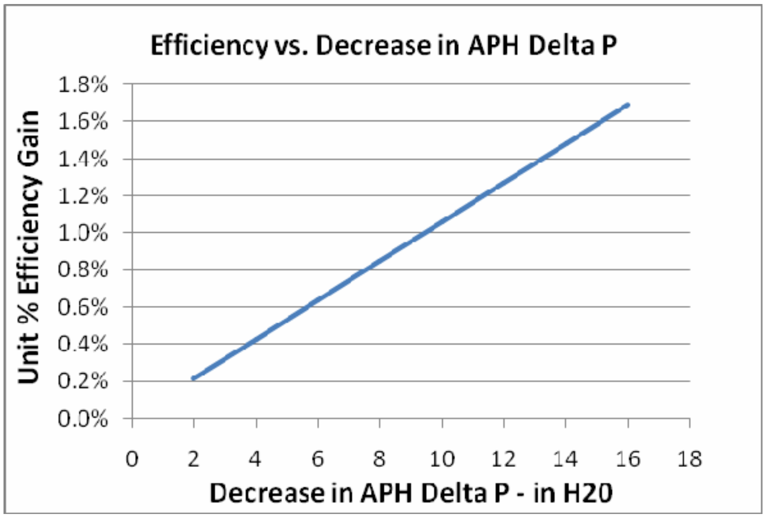

Figure 4-2
Effect of APH Pressure Drop. Example: Cleaning System Upgrade

- APH Leakage – Figure 4-3 shows the effect of reducing APH leakage on unit efficiency. Leakage increases gas flow and imposes added pressure drop on downstream equipment, such as air pollution control devices (APCDs). For illustration purposes, the graph shows the effect of a change in APH leakage for two typical APCDs. Further, it assumes that the APH design basis is 6% leakage.
  - Fabric filter at a normal ΔP of 6 in H_20
  - FGD at a normal ΔP of 10 in H_20

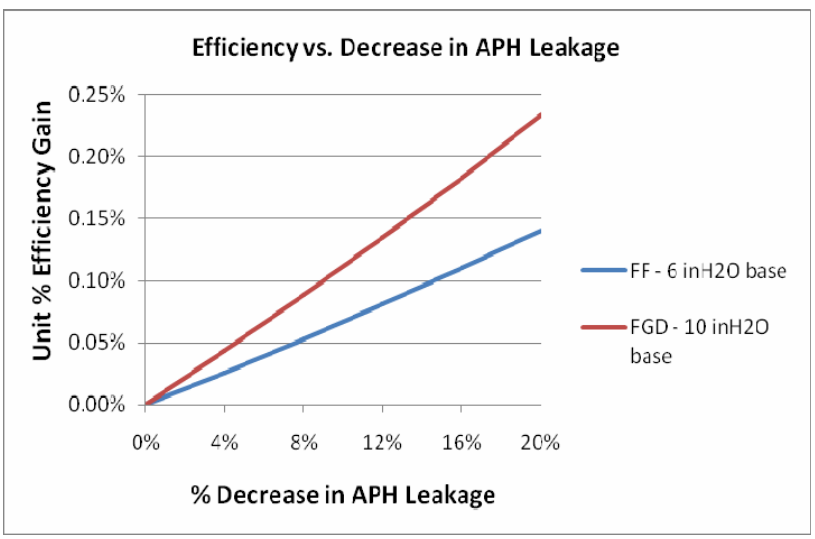

Figure 4-3
Effect of APH Leakage. Example: Seals Upgrade.

Summarizing these three primary examples of APH performance improvements, it is clear that there is potential for significant impact on heat rate. By way of an example (see more details in cost/benefit section), consider the combined effects of reducing APH gas temperature from 340ºF to 300ºF (40ºF), decreasing APH ΔP from 12 in H_2O to 6 in H_20 (6 in H_2O) and leakage from 10% to 6% (4%). From the graphs, the combined improvement in unit heat rate or fuel savings would be approximately 1.0% + 0.65% + 0.05% (FGD case) for a total of 1.7% decrease in heat rate (or 1.7% in fuel savings).

CO_2 Emissions

Another area of potential future cost benefit from the improvement of plant heat rate is the value of CO_2 credits. CO_2 emissions are directly proportional to the quantity of fuel used. Figure 4-4 presents the relationship between coal fired and CO_2 generated for a nominal bituminous coal. Figure 4-5 shows CO_2 emissions as a function of heat rate improvement for several nominally sized coal plants.

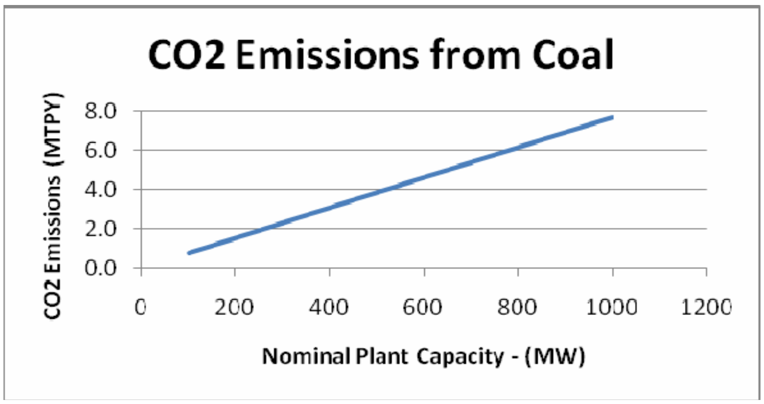

Figure 4-4
CO_2 Emissions from Coal

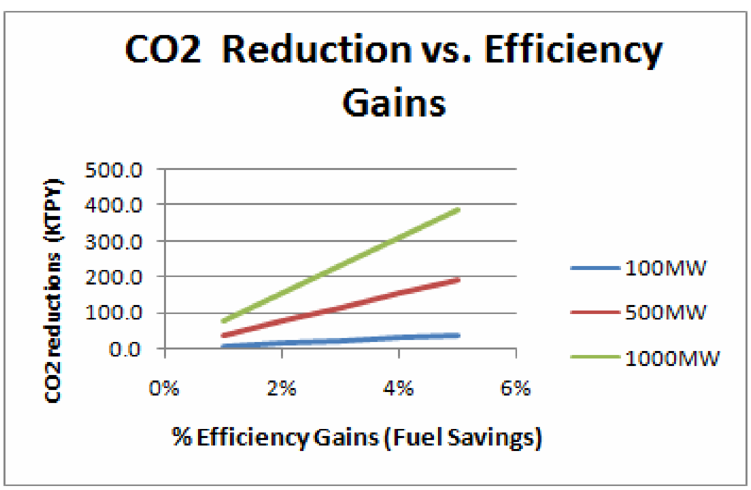

Figure 4-5
CO_2 Emissions Reductions from Increased Efficiency

The potential value of CO_2 reduction can be seen from Figure 4-5. For example, assuming a CO_2 credit of $20/ton, a 500-MW plant that reduced its heat rate by the same 1.7% as in the example above would save about 65 KTPY of CO_2, with a value of $1.3 million/year.

Cost Savings

Ultimately, these performance improvements translate to operating cost savings. The cost savings are site specific, but can be estimated using the resulting fuel cost savings due to heat rate improvement. These are directly related to the APH performance effects on heat rate. However, other operating costs must also be taken into account based on site operating experience with APH historical maintenance, etc. For example, reduced outages or cleaning cycles translate to reduced operating costs. Further, cost effects such as the potential recovery of lost capacity due to fan limitations must also be addressed on a case-by-case basis.

Translating these efficiency improvements to fuel cost savings requires assumptions for cost of fuel, plant heat rate and coal heating value. Figures 4-6 (a-b) and 4-7 provide cost savings (fuel costs) for three nominal plant sizes and three nominal coal prices. For the examples in Figures 4-6 to 4-9, plant heat rate and coal HHV were assumed to be 10,000Btu/kwhr and 12,000Btu/lb, respectively.

Similarly, the potential value of CO_2 credits can be estimated. Using the data in Figure 4-5 and assigning values to CO_2 credits ($/ton CO_2), the value of CO_2 reductions is presented in Figures 4-8 and 4-9 for the same three unit sizes and a range of CO_2 credit prices from $20/ton to $40/ton.

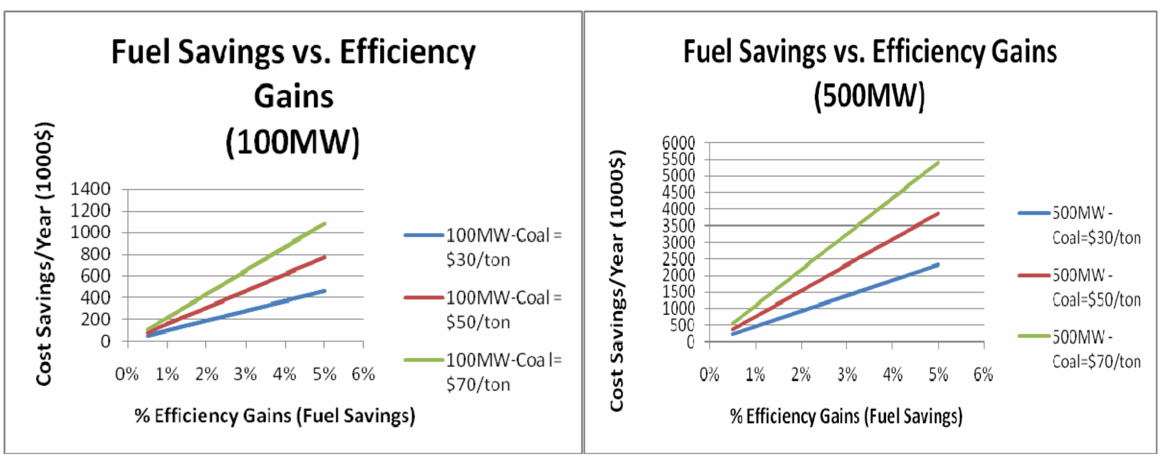

Figure 4-6
Yearly Cost Savings from Fuel Costs vs. Heat Rate Improvement
a) 100-MW unit; b) 500-MW unit

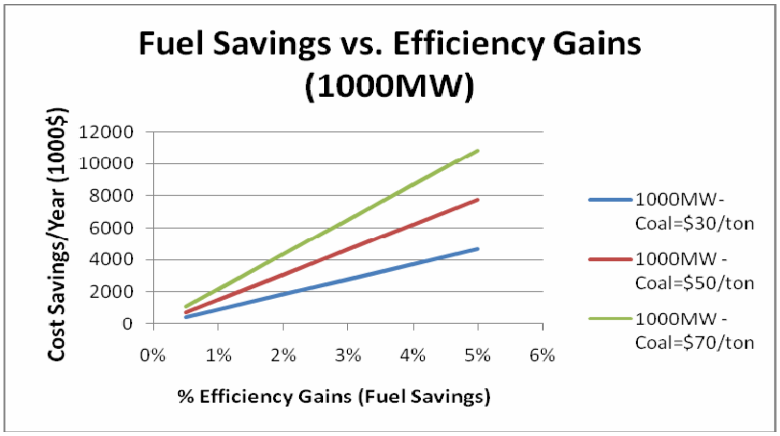

Figure 4-7
Yearly Cost Savings from Fuel Costs vs. Heat Rate Improvement (1000-MW Unit)

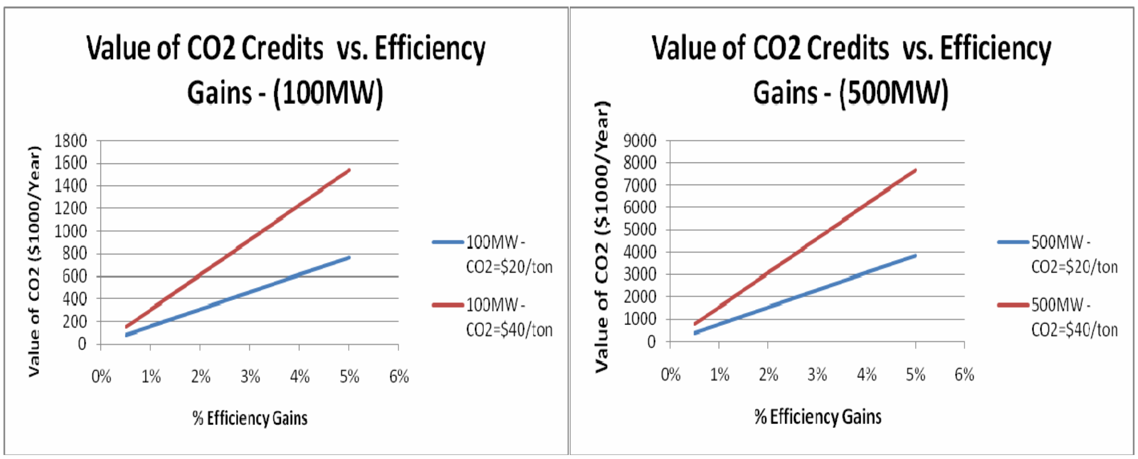

Figure 4-8
Yearly Cost Savings from CO_2 Credits vs. Heat Rate Improvement
a) 100-MW Unit); b) 500-MW Unit

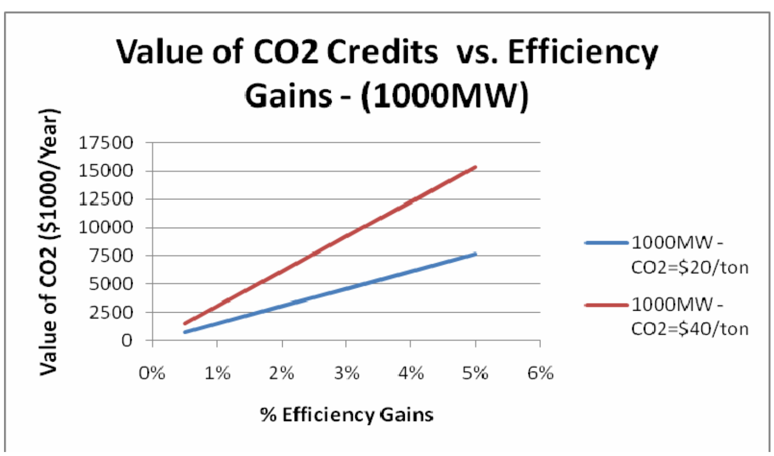

Figure 4-9
Yearly Cost Savings from CO_2 Credits vs. Heat Rate Improvement
(1000-MW Unit)

The potential cost savings from APH improvements can be significant, as shown in the graphs above. Using the same example of a hypothetical retrofit that results in a 1.7% heat rate improvement, a 500-MW unit would derive fuel savings between about $790K and $1.8M per year (for the assumed fuel cost range of $30/ton to $70/ton), and generate CO_2 credits worth between about $1.3M and $2.6M (for the assumed CO_2 credit value range of $20/ton to $40/ton).

APH Upgrade Costs

Cost for these common APH retrofits (seals, baskets, cleaning systems) were not sought in great detail, given the general scope of this study. However, some general cost ranges are provided here, based on vendor communications, as well as data provided in the answers to the questionnaire. These are not intended for use in actual cost/benefit analyses, rather just as general references to provide a basis for a hypothetical cost/benefit example. The numbers reflect typical APH size ranges and are given for typical materials and installation costs in 2008.

- Capital costs for material
  - Seals – $40K – $200K
  - Baskets – $500K – $1.5M
  - Cleaning systems – $100K – $200K
- Installation costs
  - Seals – $40K – $200K
  - Baskets – $250K – $1M
  - Cleaning systems – $50K – $100K

Cost/Benefit Example

A hypothetical cost/benefit analysis is discussed below to illustrate the potential value of an early decision for an APH upgrade, instead of using a conventional schedule-based approach. As the example here is totally hypothetical, the intent is to lay out a general process to ensure that the major considerations are included.

Plant/Unit Situation Overview

- 500-MW unit
- Two Bisector APHs
- 10,000 Btu/kwh Heat Rate
- Capacity factor – 70%
- 12,000 Btu/lb coal – (changed from 3.0% S to1.5%-2.0% S two years ago)
- Coal price – $50/ton
- CO_2 value – $20/ton
- Sufficient fan capacity – i.e., full load can be achieved
- SCR installed two years ago
- Air Pollution Control

- ESP (ΔP – 2 in H_2O)
- Wet FGD (ΔP - 10 in H_2O)

APH Situation

- Three-layer design
- No upgrades for SCR
- Seals changed four years ago
- Next scheduled outage – three years
- Original conditions
  - ΔP – 6 in H_2O
  - % leakage – 6%
  - Gas outlet temperature – 330ºF
- Current conditions
  - ΔP – 12 in H_2O
  - % leakage – 10%
  - Gas outlet temperature – 340ºF
- Summary – decision not to upgrade at time of SCR installation. ABS fouling controlled by low ammonia slip, aggressive sootblowing and yearly off-line APH washes.
- Opportunity to consider APH upgrades before next outage due to
  - High ΔP and leakage
  - Lower-sulfur coal should allow for lower gas temperature (lower acid dew point and lower ABS formation temperature)
  - Likely potential for increasing ammonia slip as SCR catalyst ages

Analysis

The challenge in this situation is to determine whether to continue current operations until the next scheduled outage or to justify an early APH outage to recover lost performance. In this case, three areas of improvement would be possible:

- Reduce ΔP through a more effective cleaning system and possibly a layer configuration change (three-layer to two-layer with a deeper cold end for better sootblowing effectiveness).
- Reduce leakage through better seals.
  - Note that typical APH leakage testing by O_2 balance does not address circumferential or bypass leakage, which does not contribute to the O_2 imbalance but does affect APH heat transfer effectiveness. Visual inspection of bypass openings and/or detailed heat transfer analyses might be appropriate in some cases.
- Reduce gas temperature through reduced leakage and more efficient basket heating elements.

Having determined these areas for improvement, the justification process should include the following major steps and analyses:

- Technical
  - Determine targets for the major parameters (suggested values only for use in hypothetical example)
    - ΔP – 6 in H_2O (must reconcile heat transfer, rotor size and basket plate design)
    - % leakage – 4% (consider the various seal designs available)
    - Gas temperature – 300ºF (determine minimum acceptable gas temperature based on acid dew point for current coal and on ABS formation for NH_3 and SO_3 conditions)
  - Determine efficiency gains from target levels compared to current operation (e.g., as per the graphs above)
- Costs of APH upgrade
  - Capital /Installation
  - Outage costs (site-specific energy, capacity, purchased power)
- Benefits from APH upgrade
  - Fuel savings from heat rate improvement (including all contributions as discussed above)
  - Value of CO_2 credits (if applicable)
  - Recovered capacity (if applicable)
  - Reduced APH washes (if applicable)
  - ESP performance due to lower temperature and gas flows (if applicable)

Key Results

For illustration purposes, key costs/benefits for this example are shown below.

- Costs
  - Seals – $300K
  - Baskets – $1.5M
  - Cleaning systems – $200K
  - Outage cost – site specific
    - Total (not including outage cost) – $2M
- Benefits
  - ΔP reduction – 0.65% heat rate (from Figure 4-2)
  - Leakage reduction – 0.05% heat rate (from Figure 4-3)
  - Gas temperature reduction – 1.0% heat rate (from Figure 4-1)
    - Total – 1.7% heat rate improvement
    - Total fuel savings – ~$1.3M/yr (from Figure 4-6b)
  - CO_2 value (if applicable) – ~$1.3M/yr (from Figure 4-8b)
  - Recovered capacity (if applicable)
  - Reduced APH washes (if applicable)

- ESP performance due to lower temperature and gas flows (if applicable)

Discussion

This simplified example highlights the major considerations appropriate for an APH upgrade analysis. The key message is that APH O&M upgrades can be justified on a condition basis as opposed to a schedule basis. The importance of fuel efficiency and the potential value of CO_2 reductions are the main drivers towards increased awareness of APH performance and its major effect on plant heat rate. The first-order effects are highlighted in this example. The other, non-quantified impacts (outage costs, recovered capacity, reduced washes, etc.), are equally important in the overall analysis and can affect the cost/benefit decision. In this example, the three-year savings of doing an early APH upgrade are between $3.9M (fuel savings only) to $7.8M (including CO_2) compared to a capital cost of $2.0M, for a simple payback of about 1.5 years for fuel alone, or about eight months if CO_2 is included.

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