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TECHNICAL
REPORT

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Performance of a Condensing Heat Exchanger System at Lake City Army Ammunition Plant, Independence, MO

by
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U.S. Army Engineering and Housing Support Center
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Innovative Ideas for the Operation, Maintenance, & Repair of Army Facilities

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13. ABSTRACT (Maximum 200 words)
The U.S. Army has placed high priority on conserving national energy resources and is particularly interested in projects that demonstrate energy conservation. Approximately 18 percent of the fuel energy put into a boiler is wasted in the form of heat in the flue gas. This excess heat is necessary to maintain the flue gas temperature above the dewpoint of sulfur oxides to prevent corrosion.

Because the condensing heat exchanger (CHE) system is resistant to corrosion, it allows the flue gas temperature to be reduced and the waste heat to be recovered, potentially increasing fuel efficiency. To evaluate the potential savings, the U.S. Army Construction Engineering Research Laboratory (USACERL) conducted a system demonstration on the most frequently used boiler at Lake City Army Ammunition Plant (Army Materiel Command [AMC], Independence, MO.

Researchers estimated the annual fuel savings to be $132,000 based on 5 months of measured data, at a fuel cost $3.92. per million Btu. The total investment for the CHE system including installation was $199,200. The attractive payback of 1.5 years on the initial investment demonstrates the opportunities associated with CHE systems and warrants a broader investigation of applying the technology throughout AMC and the Army.

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FOREWORD

This work was performed for the U.S. Army Engineering and Housing Support Center (USAEHSC) under the Facilities Engineering Applications Program (FEAP), Project FH1, "Heat Recovery at Industrial Facilities." The USAEHSC technical monitor was Mr. S. Sharma, CEHSC-FU-M.

System monitoring and overall project management was conducted by Sharon Jones and Richard Caron of Arthur D. Little, Inc., Cambridge, MA. Engineering and construction was performed by Ronald Messen of Steam Plant Systems, Inc., Clifton Park, NY, under the direction of the U.S. Army Construction Engineering Research Laboratory, Energy Systems Division (USACERL-ES). Dr. Dave Joncich is Chief, USACERL-ES. The technical editor was Gloria J. Wienke, USACERL Information Management Office.

The cooperation of Mr. John Swanson of Olin Corporation, operating contractor at Lake City Army Ammunition Plant, is gratefully acknowledged.

COL Daniel Waldo, Jr., is Commander and Director of USACERL, and Dr. L.R. Shaffer is Technical Director.

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1 INTRODUCTION

Background

The Army Materiel Command (AMC) uses one-fourth of the Army's facilities energy in the course of its broad mission of providing materiel support. About half of AMC's energy requirement is for process energy used throughout a vast complex of industrial facilities. Since both the short- and long-term trends suggest persistent high energy prices, the Army and AMC are particularly interested in projects that have the potential to increase fuel efficiency and energy conservation. The Facilities Engineering Applications Program (FEAP) promotes demonstrations of technologies that, although theoretically cost effective, might not otherwise be tried at Army facilities because of their novelty.

Approximately 18 percent of the fuel energy put into a boiler (depending on the fuel used) is wasted in the form of sensible and latent heat in the boiler flue gas. Much of this energy (6.5 percent for oil fired units and 9.5 percent for gas units) is in the form of latent heat (water vapor). With conventional economizers and steel stacks, this waste heat is necessary to maintain the flue gas temperature above the dewpoint of sulfur oxides to prevent corrosion. To further reduce the flue gas temperature and achieve higher overall performance, a heat exchanger system capable of operating below the sulfur oxides dewpoint is required. Condensing heat recovery systems are protected from corrosion, allowing the flue gas temperature to be reduced below the dewpoint of sulfur oxides.

This report describes the results of monitoring a demonstration of a condensing heat exchanger (CHE) at Lake City Army Ammunition Plant (LCAAP), Independence, MO from January 19 through June 7, 1990. This demonstration was based on favorable results of a smaller scale demonstration at Louisiana Army Ammunition Plant, Shreveport, LA.[1] This demonstration was cofunded by the U.S. Army Engineering and Housing Support Center (EHSC), AMC, and LCAAP. Engineering and construction was performed by Steam Plant Systems, Clifton Park, NY. Monitoring and overall project management was conducted by Arthur D. Little, Inc., Cambridge, MA.

Objective

The primary objective of this study was to evaluate and demonstrate condensing heat exchanger technology on a large, gas/oil process-steam boiler at Lake City Army Ammunition Plant. The experimental test program was designed to account for variations in boiler loading due to changing weather and steam demand.

[1]Michael P. Case, et al., *Performance of a Condensing Heat Exchanger in Recovering Waste Heat From a Natural Gas-Fired Boiler*, Technical Report E-90/09/ADA222456 (U.S. Army Construction Engineering Research Laboratory [USACERL], May 1990).

Factors Influencing Feasibility

The overall attractiveness of a CHE depends on the following criteria:

- Thermal efficiency of existing units. The lower the original unit's efficiency, the higher the economic benefit of installing a CHE.

- Unit operating load. Daily and seasonal variations in load.

- Fuel cost and fuel type. The higher the moisture content of the fuel, the more latent heat theoretically can be recovered. In addition, the higher the sulphur content of the fuel, the more difficult it is to recover waste heat with conventional economizers.

- Available heat sinks. The type and temperature of the sink, the amount of energy that can be transferred to the sink, and the variations of sink capacity with time.

- Available heat sources. The flue gas flow rate, temperature, and composition, considered with heat sink conditions.

- Arrangement of existing equipment. Flue gas duct arrangement and available space for the CHE and associated equipment affects both the design and the system cost.

- Cost of equipment and installation. The cost depends on the size of the CHE, equipment arrangement, strength of the floor or roof supporting the CHE, and other site-specific requirements.

- Environmental impacts. Benefits of reduced particulate and sulfur compound emissions in the flue gas, and issues associated with the disposal of CHE effluent, changes in flue-gas dispersion, and impact of initial construction.

Approach

Lake City Army Ammunition Plant was selected as the demonstration site based on a good combination of the factors listed above and the applicability evaluation in Appendix A. After the LCAAP site was defined, the CHE was selected and installed with metering. Data collection and analysis followed.

Mode of Technology Transfer

The results of this demonstration will be disseminated through a FEAP User Guide. The User Guide will contain information on acquiring the technology, as well as data for calculating the payback and applicability to the user's installation. Articles describing CHE technology and its benefits have also appeared in the DEH Digest.

2 PROCEDURE

Existing Site Situation

The steam plant at Lake City supplies steam for process heating, cleaning, comfort heating, and domestic hot water. The plant has four boilers. As the workhorse of the plant, boiler #4 is the newest and largest boiler and is the only one without an economizer. Therefore, it was the logical choice of heat source for the heat recovery system.

Boiler #4 is a 1973 dual-fuel (gas/No. 6 oil) water-tube boiler rated for 80,000 pounds per hour (lb/hr)* of 200 pounds per square inch, gauge (psig) saturated steam. Typically, boiler #4 operates September through June supplying an average of 47,300 lb/hr of steam (70 percent of the steam requirement) at 150 psig. The flue gas temperature ranges from 350 to 380 °F. The steam plant uses makeup water combined with returned steam condensate and preheated with steam in a deaerator before going to the boiler as new feedwater. Figure 1 shows a block diagram of the boiler system layout before the CHE was installed.

The steam-heated deaerator serves two purposes: it preheats the water being fed to the boiler, and it scrubs the water of potentially corrosive dissolved oxygen. Water fed to the deaerator is heated approximately to the temperature of saturated steam. Since oxygen solubility is very low under such

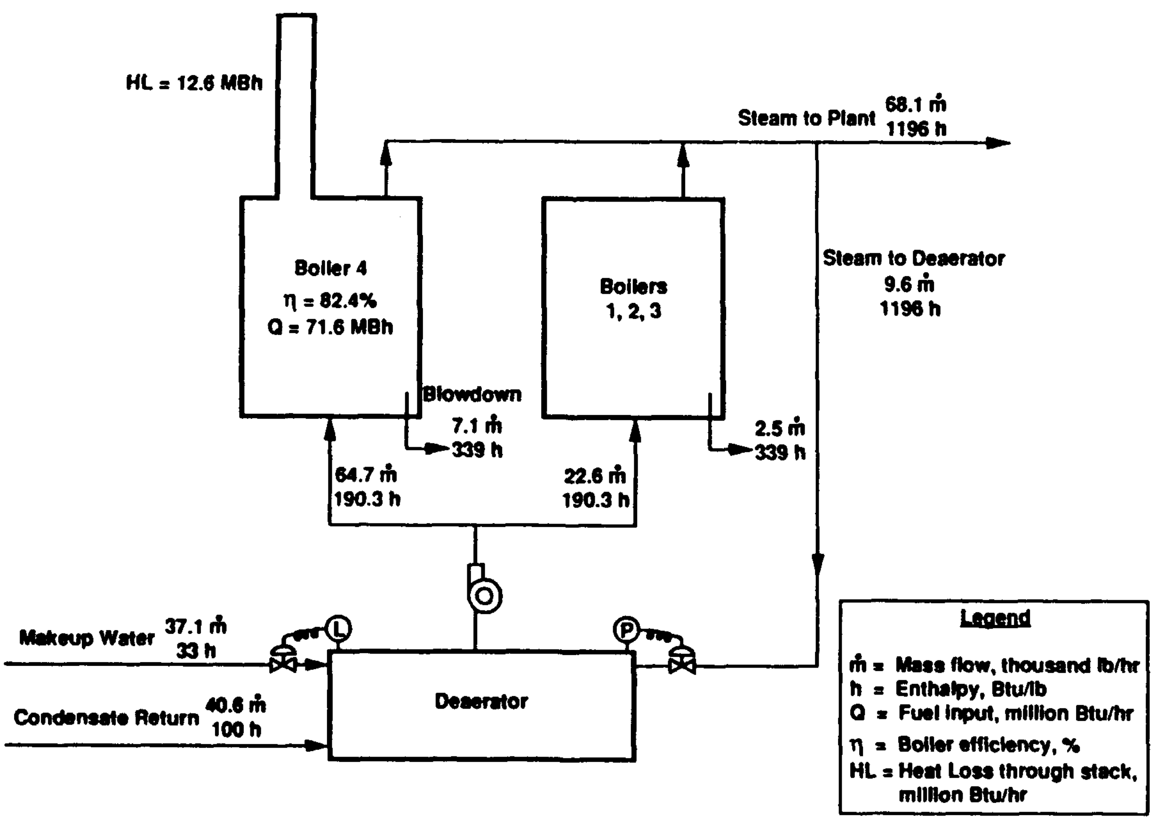

Figure 1. Existing Site Schematic.

*A metric conversion table is provided on p 23.

conditions, 97 to 98 percent of the oxygen is released to the steam and then vented away. The deaerated water is then suitable for feeding the boiler. The CHE reduces the steam required for the deaerator by supplying it with preheated makeup water.

Heat Recovery System Description

The heat recovery system consists of a heat exchanger, supply and return water piping, supply ducting with a damper and fan, an exhaust stack, and necessary controls for operation.

Condensing Heat Exchanger Overview

The condensing heat exchanger is a mechanical unit that uses the waste heat in the boiler flue gas to preheat boiler makeup water. The flue gas flows over tubes that carry the makeup water to be heated. The quantity of heat transferred is limited by the heat available from the flue gas and/or the heat requirement of the makeup water.

A CHE is ideal for this application because it can take advantage of waste heat below the sulfur dewpoint temperature, since it is coated and can tolerate the corrosive effects of condensing flue gas. The system can therefore cool the flue gas below its dewpoint, permitting latent heat extraction from the water vapor present in the flue gas.

Heat transfer depends on the temperatures, flow rates, and heat transfer coefficients of the heat sink and heat source. The most effective combination takes maximum advantage of these factors. The boiler flue gas, as the heat source, is relatively well defined; the challenge is to find available heat sinks that can effectively use the recovered heat stream.

Since liquids have higher heat capacities and heat transfer coefficients than gases, the most desirable heat sink is typically the lowest-temperature water available at a reasonable flow rate. Therefore, makeup water is often the first choice of heat sink for condensing heat recovery. However, if there is substantial condensate return, the makeup water flow rate may not be conducive to cost-effective heat recovery.

Combustion air can also be preheated via condensing heat recovery, but this option generally is not as attractive as preheating makeup water or other liquids. The low heat capacity of air and the smaller heat transfer coefficient necessitate larger, more expensive heat exchangers to accommodate both the heat-transfer surface requirements and the large volume of combustion air. Additional problems are presented by requirements for large and often lengthy ductwork, or in some cases, use of paired exchangers.

In the LCAAP application, makeup water was readily available at flow rates of 50 to 100 gpm and relatively low temperatures of approximately 65 °F to use as a heat sink. Makeup water for the steam plant housing four boilers was preheated using the flue gas from boiler #4.

Heat Exchanger Selection

The CHE itself is the heart of the system and it's selection is critical to the life of the system. Condensing heat exchangers are designed to reduce the flue gas temperature to below 200 °F, a point where not only sulfuric acid (if sulfur is present in the fuel) but also water vapor condenses on the tubes creating a highly corrosive environment. The challenge of condensing heat recovery is to provide a heat exchanger that can withstand this environment.

Condensing heat exchangers on the market use glass, graphite, stainless steel, or Teflon® to protect the tubes (where most condensation occurs) and glass, stainless steel, or Teflon® to protect the shell of the heat exchanger from corrosive attack.

Glass (Pyrex®) exchangers have a good track record; however, glass tubes might break due to the pressure difference between the water inside the tubes (~60 psig) and the gas outside the tubes.

Graphite—Viton exchangers introduced in 1987, appear promising. Although researchers selected a proven performer for this demonstration, future efforts should investigate graphite—Viton exchangers.

Stainless steel exchangers are offered by one company. The heat exchanger has promise, and the manufacturer has significant experience in the chemical process industry, but has little experience with boiler flue gas. The manufacturer's lack of experience with boiler systems would increase the design effort and the risk of inadequate system design. This system requires further study to determine acceptability to condensing flue gas heat recovery.

The heat exchanger chosen for this FEAP demonstration is a Teflon®—Teflon® exchanger supplied by CHX® Corporation, Warnerville, NY. The tubes and shell are Teflon covered. The CHX® heat exchanger is 12 ft high by 5.3 ft deep by 4.8 ft wide, and provides a heat transfer surface area of 1590 sq ft. It weighs 6772 lb when empty and 9017 lb with water in the tubes. The unit is composed of five modules each with 240 horizontal tubes in an 8 by 30 arrangement; each tube is 60 in. long. Minimum water flow rate is 22.5 gallons per minute (gpm). See Appendix B for complete CHX® specifications.

Flue Gas Flow

Figure 2 shows a simplified schematic of the installation arrangement with the CHE in place. The flue gas enters the heat recovery system through a new breaching in the existing stack, then flows past a flue-gas damper, through an induced draft fan, down through the heat exchanger, and exits up through a fiberglass-reinforced plastic stack.

The damper controls flue-gas flow through the CHE to maintain the exit water setpoint temperature. If there is more flue gas available than needed to heat the makeup water fully, the excess flue gas continues up the preexisting stack. Otherwise, all of the flue gas flows through the CHE and a small amount of outside air is drawn down the preexisting stack. The fan is provided to overcome the pressure drop through the heat recovery system. This is a passive system since no obstruction is placed in the existing flue-gas passages. This damper also shuts down at a high flue gas inlet temperature (setpoint = 450 °F) due to the maximum temperature limit of the Teflon.

A drain is provided on the flue gas side for the water vapor and acids that condense on the CHE tubes. The condensate and the CHE washwater are highly acidic and cannot typically be drained to a sewer because of their corrosiveness. Commonly accepted practice is to pipe the CHE drain to the boiler blowdown sump since boiler blowdown is highly alkaline and neutralizes the condensate. Note that environmental regulators generally establish thermal and chemical property limitations on wastewater effluents at the point of discharge. Typically, the CHE condensate is so small as to be negligible when combined with other wastewater effluents. However, local regulations may vary and some may require CHE condensate pretreatment.

Makeup Water Flow

On the water side, a booster pump overcomes the additional pressure drop of the CHE and its associated piping. The water outlet temperature setpoint is 160 °F to ensure that water to the deaerator is not overheated. Furthermore, at high exit-water temperature (180 °F) the entire system shuts down to protect the heat exchanger from steaming, over-pressure, or scale buildup on the tube side.

The system also shuts down on low water flow. In a low-flow or no-flow condition, the high exit-water temperature measurement may not accurately indicate the temperature of water in the tubes since the water further upstream could be at a higher temperature than the water in the outlet manifold.

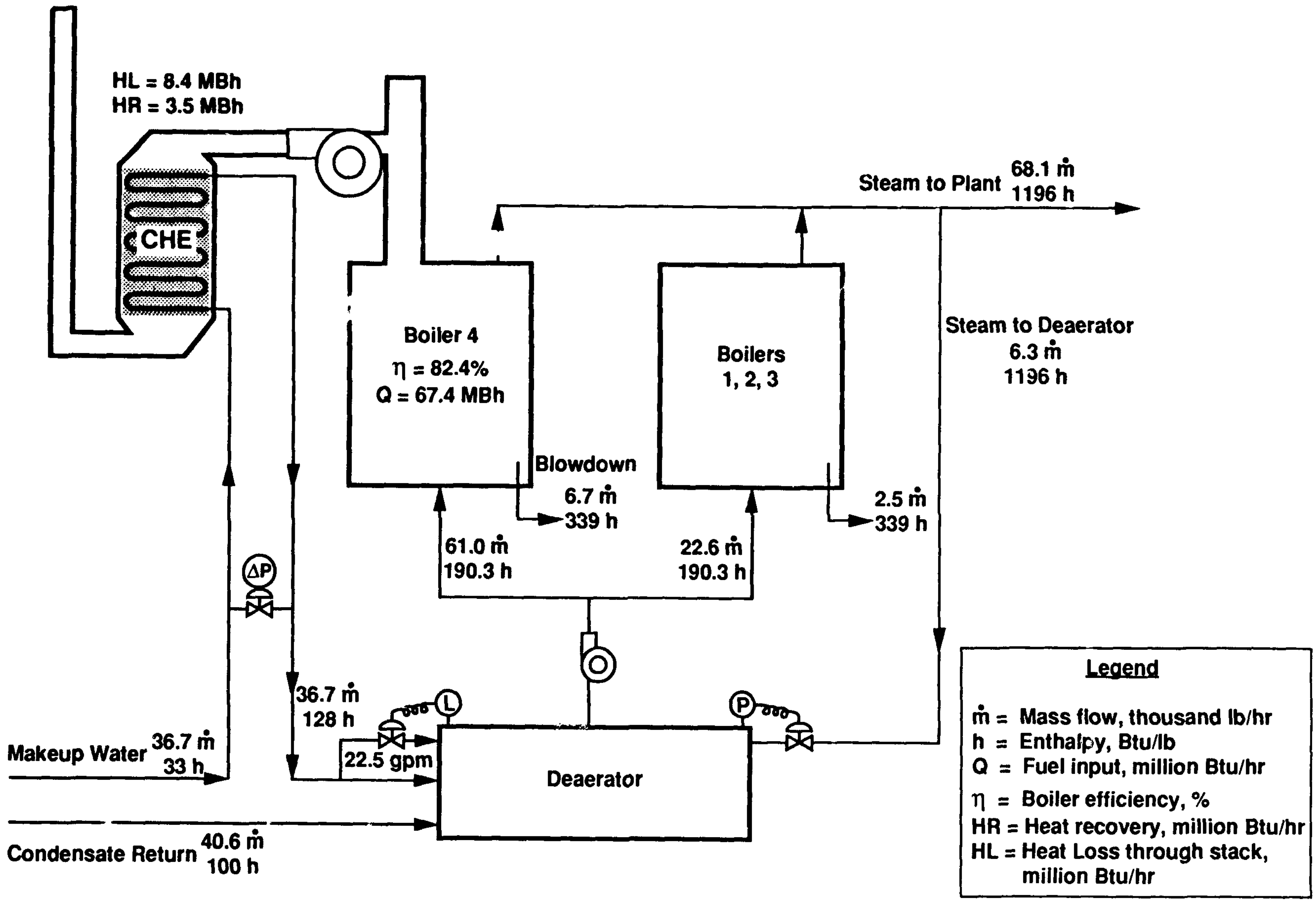

Figure 2. Site Schematic With CHE Installed.

These controls require that special care be taken in the system design to provide adequate water flow and prevent nuisance shutdowns. One issue addressed at Lake City was that condensate is returned to the boiler plant in surges caused by the cycling of large condensate return pumps. This causes the level control on the deaerator to briefly shut off the makeup water flow, which interrupts the flow of water to the heat exchanger. The situation was intermittent, but it could occur several times an hour.

One approach to preventing frequent shutdowns is to install a storage tank and circulating water loop. For this demonstration, researchers pursued a less costly approach consisting of installing a bypass line around the makeup water control valve to allow a small amount of makeup water (approximately 22 gpm) to flow continuously through the CHE and into the deaerator. This approach, however, inherently has the risk of overflowing the deaerator. There were already two sources of uncontrolled water flow to the deaerator (condensate return and boiler feed-pump turbine steam discharge); now there are three. So far, researchers have not observed a problem of water overflow from the deaerator. However, on a few warm days in early June 1990, the steam requirement of the deaerator, with preheated makeup water from the CHE, was less than the steam discharge from the boiler feed-pump turbine. Rather than vent the excess steam to the atmosphere, researchers shut down the CHE so the boiler feed-pump turbine discharge steam could be fully used.

The maximum water flow through the CHE is 125 gpm at a 20 psi pressure drop. This allows all of the makeup water to be preheated under usual circumstances. However, if all boilers were operated at maximum output, such as might occur during mobilization, there would not be sufficient water flow through the CHE to satisfy the makeup water requirement. To accommodate this situation, researchers installed a pressure-activated bypass valve to bypass additional makeup water around the CHE in the event of makeup water demand greater than 125 gpm.

Instrumentation

Heat recovery monitoring instrumentation consisted of a water meter, two thermistors, and a Btu computer to calculate and display the cumulative flow and enthalpy increase of makeup water through the CHE.

The selected turbine water, a 3-in. Badger Turbo meter, provides a pulse output for each 10 gal processed through the meter and is accurate to ± 0.5 percent over the range 60 to 350 gpm.

High precision thermistors were installed in the inlet and outlet water manifolds. These YSI brand thermistors (model 44036) are interchangeable to ±0.2 °F for a maximum measurement error of about 0.5 percent on an 80 °F temperature differential.

The signals from the flow meter and the water inlet and exit thermistors are registered on a DK Enterprises Btu computer. An internal microprocessor with a digital staircase integrating board uses this information to compute the Btu change in the flowing water stream within ±0.4 percent.

Lake City boiler operators recorded Btu meter, CHE, and boiler plant information daily. Data sheets were collected at the site and transmitted to Arthur D. Little by telefax weekly. Figure 3 shows a sample data sheet used during monitoring.

CERL - CHX DATA SHEET

Site: Lake City AAP

Boiler 4

Technician William Thurman

Date 1-21-90 Sun

	READING	START	FINISH	CALC (For ADL Use)	
1	Date	1-21-90	1-22-90		
2	Time of Day	12:02 am	12:45 am	23.95 hr	
3	O.S. Temp (°F)	29°	37°		
4	Makeup (Gallons)	Ø			
5	Differential Temperature (°F)	0°	1°		
6	Water Out Temperature (°F)	156°	160°	105° ΔT	ind.
7	Water In Temperature (°F)	56°	55°	98.5° ΔT	calc.
8	Flue Gas Out Temperature (°F)	137°	126°		
9	Flue Gas In Temperature (°F)	386°	380°		
10	Water Flow (GPM)	90	52	82.5 gpm	ind
11	Water Volume (Gal x 10)	68700	80577	11877	
12	Heat Recovered (Btu x 10^4)	45870	55624	9754	
13	Flue Gas Diff Pressure ("wc)	4.0 ?	.50	4.06 mBh	
14	Water Diff Pressure ("wc)	10.5	4.0		

	BOILER	1	2	3	4	TOTAL
15	Hours		24		24	
16	Steam Flow		1099200		1106800	
17	Gas Flow		1227600		1252900	
18	Excess Air		3.2		3.4	
19	Stack Temp (°F)		347		375	
20	Efficiency		93 %		92 %	

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Comments

$$\frac{9754(10^4)\,Btu}{11877(10)\,gal} \cdot \frac{gal}{8.34\,lb} \cdot \frac{1\,lb\,°F}{1\,Btu} = 98.5°F\ \Delta T$$

Figure 3. Sample Data Sheet.

3 RESULTS AND ANALYSIS

Heat Recovery Determination

The degree of makeup water preheat achieved is a direct function of the heat transferred or recovered. Heat recovery may be determined either from the loss of the heat source or the gain of the heat sink, both of which are a function of temperature and flow. For this study, researchers calculated the heat gain because the flow rate of water can be measured more easily and accurately than the flow rate of flue gas.

By measuring the flow rate and the temperature differential across the condensing heat exchanger, and combining the results of these measurements with the known density and heat capacity of water, researchers calculated the amount of heat recovered.

Heat Recovery Performance

The Lake City installation is limited by the heat sink, as shown in Figure 4. In this figure, the heat source is calculated as the heat available in the flue gas based on combustion efficiency. The calculations show that the heat sink raises the makeup water temperature by 95 °F, from 65 °F to 160 °F. Site personnel selected 160 °F as the makeup water preheat temperature setpoint to ensure adequate steam loading in the deaerator for proper deaeration.

A tabulation of the results of heat recovery monitoring over the test period is presented in Table 1 for six bins of outdoor air temperature.

Over the test period (January 19 to June 7, 1990), the CHE produced an average of 3.2 million Btu/hr heat recovery from the 55.8 million Btu/hr fuel consumed by boiler #4, to support 68,100 lb/hr steam generation (covering the total plant).

Characteristics of the heat exchanger are as follows:

- Reduces bulk flue gas temperature from 365 °F to 127 °F,
- Preheats 74 gpm of makeup water from 65 °F to 160 °F,
- Transfers 3500 kBtu/hr of sensible heat and 1475 kBtu/hr of latent heat,
- Reduces steam flow to the deaerator by 38 percent.

Annual Fuel Savings

Since the heat recovered in the CHE preheats the incoming makeup water, this heat gain reduces the steam load that the system must supply to the deaerator. This reduces the volume of water being heated by the boiler, thereby saving fuel and a small amount of water that would otherwise be lost to blowdown. Consequently, fuel savings is based on the magnitude of the deaerator steam-load reduction.

The following equation (analytically derived in Appendix C), gives the daily fuel savings as a function of the heat recovery makeup water flow rate, and existing boiler efficiency. (Later this equation is applied to account for a full, "average" year.)

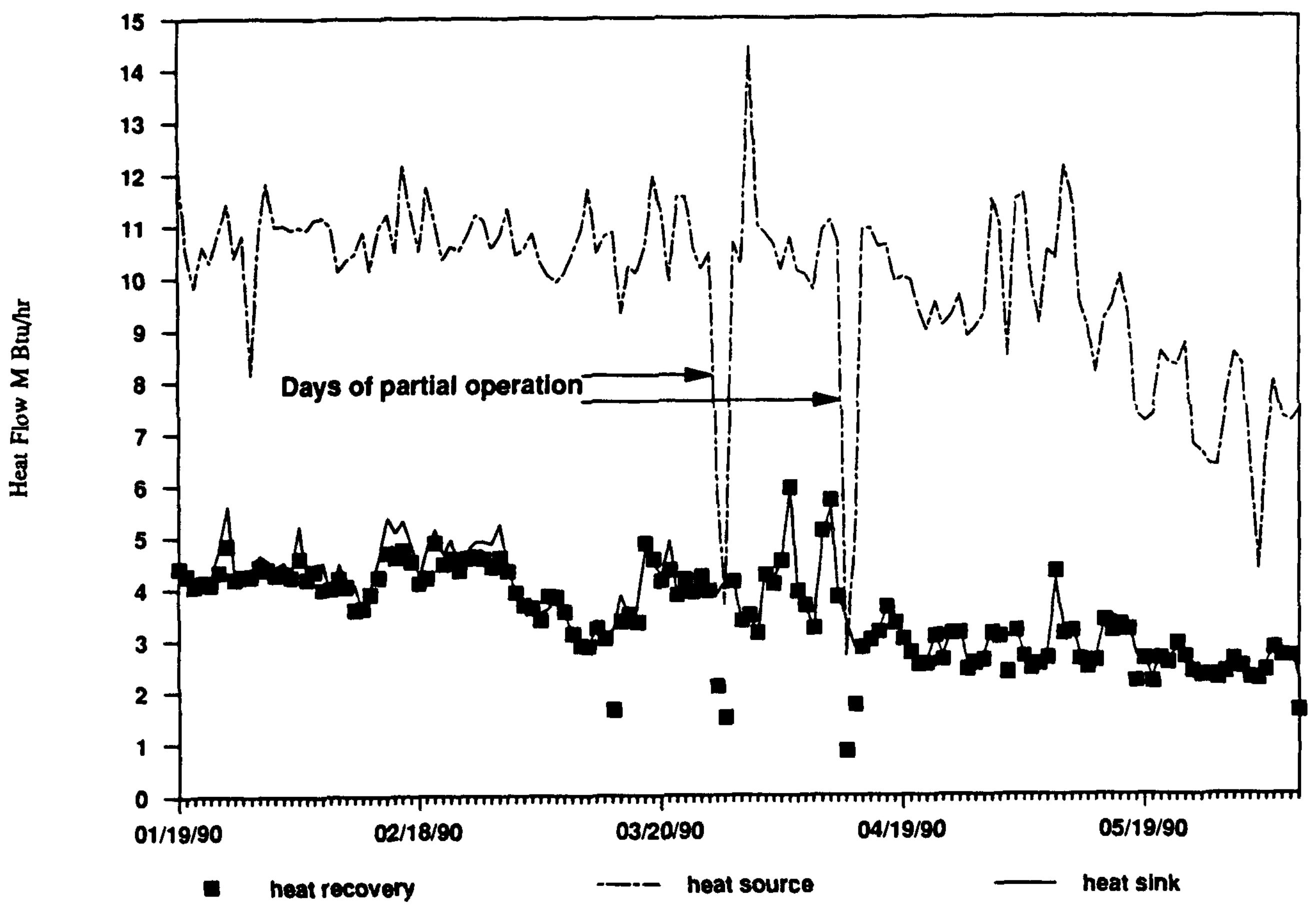

Figure 4. Daily Average Heat Flow for Test Period.

Table 1

Measured Performance During Test Period

	1	2	3	4	5	6
Outdoor temperature range, °F	75↑	70-74	62-69	50-61	37-49	36↓
Avg. outdoor recorded temp., °F	75.3	71.6	65.5	55.0	43.4	29.9
Days in range	3	8	22	29	52	26
Heat sink: makeup water						
Flow rate, gal/min	51.7	57.0	55.5	64.7	79.7	92.8
Makeup water preheat, °F	89.4	97.5	96.5	95.9	93.2	95.3
Heat source: flue gas						
Boiler 4 steam load, lb/hr	39,600	40,000	43,000	48,800	49,700	52,400
Existing efficiency, %	83.2	83.3	83.0	82.6	82.2	81.7
Heat Recovery, kBtu/hr	2300	2800	2700	3100	3700	4400

$$FS = \frac{1}{\eta}[1.037HR - 0.116m_2] \quad \text{[Eq 1]}$$

where FS = fuel savings, kBtu/hr
HR = heat recovered, kBtu/hr
η = boiler efficiency
m_2 = makeup water flow rate, kph.

As stated previously, heat recovery (HR) is a function of makeup water flow and makeup water flow tends to decrease with increasing average daily temperature. These functions have been combined to yield heat recovery as correlated to average daily temperature in Figure 5.

Boiler efficiency (η) depends on average daily ambient temperature, since it varies with excess air level, the entering combustion air temperature, and the exiting flue gas temperature (measured before the CHE). Figure 6 shows the corresponding relationship between boiler efficiency and temperature.

To determine annual fuel savings, researchers used the heat recovery/daily temperature correlation to extrapolate measured data from the 5-month test run to a full year's operation. Since changes in outside temperature affect the overall steam-load requirements, researchers applied the results to the temperature profile for an averaged "normal" year (Figure 7) and obtained the total fuel consumption/savings achievable over a full year.

Economic Analysis

Using these correlations, annual fuel savings are expected to reach 36,000 million Btu/yr.

Cost savings are calculated from the fuel savings, valued at the cost of fuel, then discounted by the parasitic energy consumption of the supporting fan and pump valued at the cost of electricity. Fan power

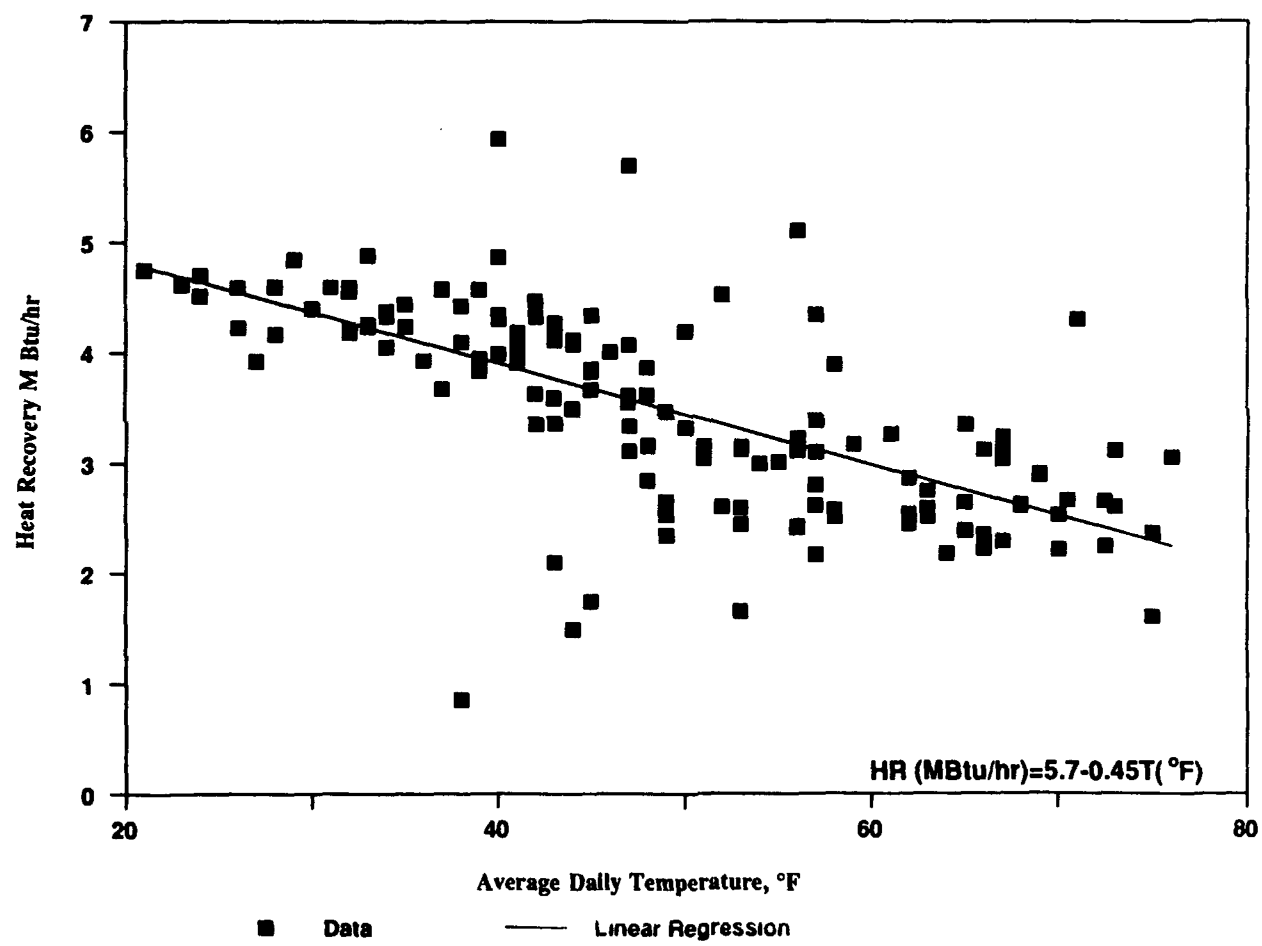

Figure 5. Heat Recovery vs Average Temperature.

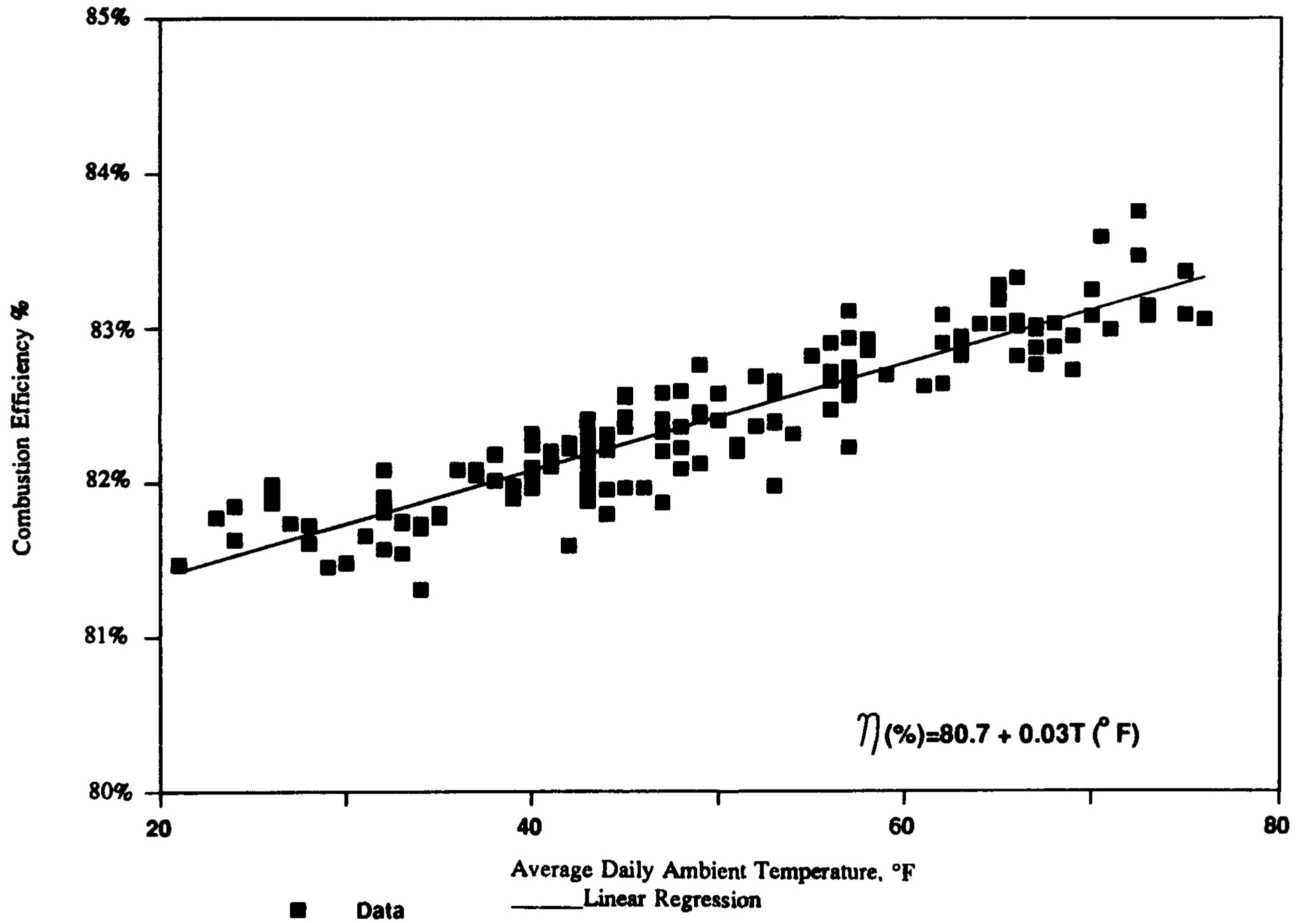

Figure 6. Boiler Efficiency vs Daily Temperature.

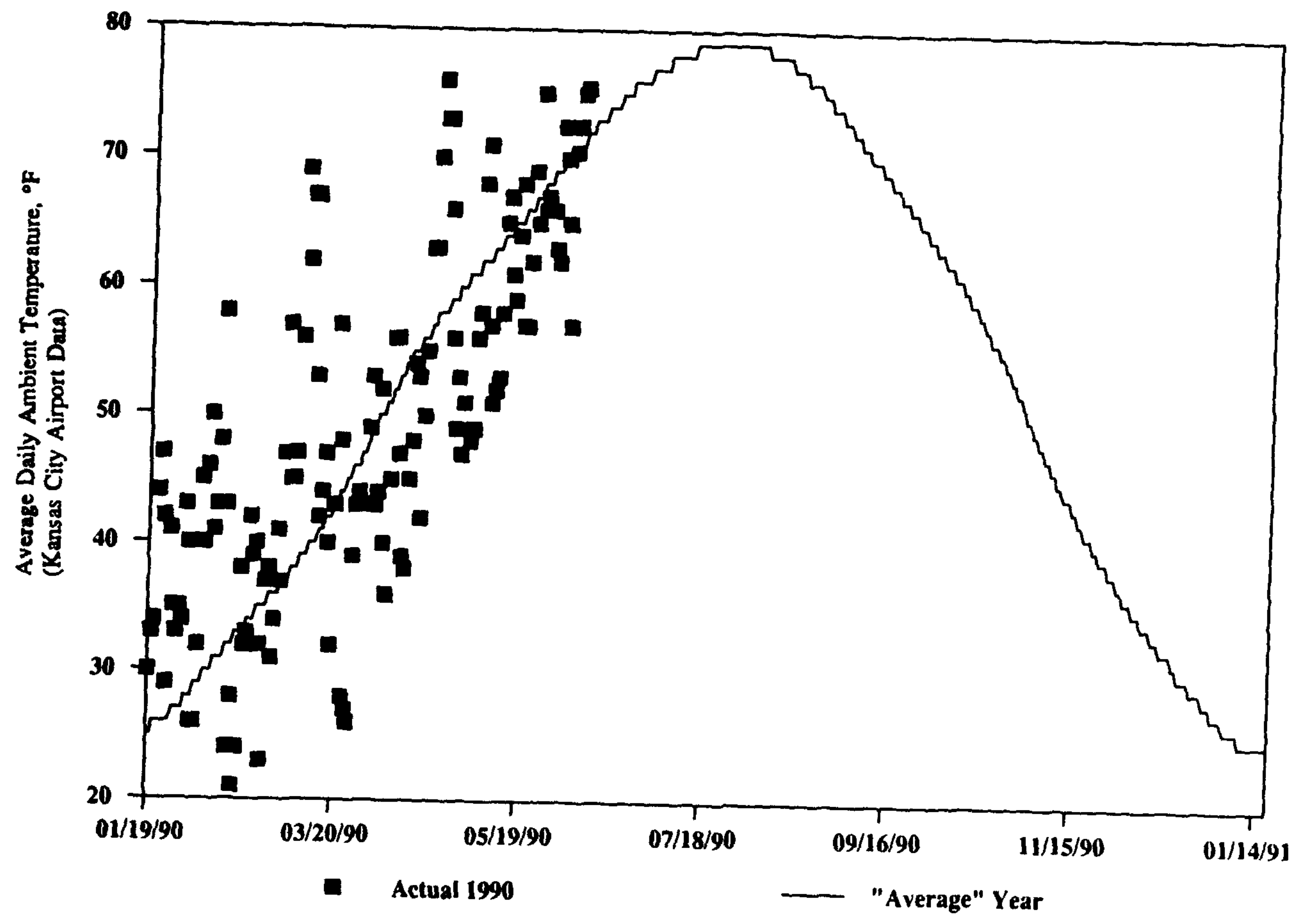

Figure 7. Annual Temperature Profile.

is estimated from the theoretical fan power requirement, which varies from 2 to 23 horsepower (hp), plus 2 hp to conservatively account for motor inefficiency and shaft losses. Pump power is estimated at a constant 1.5 hp.

With the 1990 price of fuel at LCAAP of $3.92/million Btu and of electricity at $49.50/MWh, the net savings is $132,000/yr, as shown in Figure 8 and detailed in Table 2.

Referring to Arthur D. Little's preliminary design (see Table 3), the projected net savings of $132,000 per year exceeds the original estimate of $84,310 by 50 percent. This can be attributed to increased fuel cost (40 percent increase) and future planned summer operation (12 percent increase). The thermal performance of the heat exchanger was very close to predicted values.

Simple Payback. Total cost of the installed project was $199,200 excluding monitoring and reporting efforts. With annual savings of $132,000, the simple payback is 1.5 years.

Life Cycle Cost. The CHE system is expected to last 15 to 25 years. The net present value of savings based on a 15-year life is estimated at $852,700 using a 9 percent discount rate and assuming average maintenance costs over the life of the system of $1500 per year.

Effect of Varying Parameters on Heat Recovery

The key factors affecting heat recovery performance are associated with the heat sink (makeup water) since this installation is heat sink limited. These factors are the flow rate and the maximum permissible exit-water temperature. The following sensitivity analysis indicates how these key parameters affect heat recovery.

The Lake City AAP steam plant averaged 73 gpm makeup water flow with 46 percent condensate return during the test period. Should the steam load or percent makeup increase, heat recovery increases correspondingly. Figure 9 shows how a change in makeup flow would affect heat recovery on a normalized basis. The figure shows that an increase in makeup water flow from 73 to 80 gpm would increase heat recovery and fuel savings by 10 percent.

Researchers selected the maximum permissible exit-water temperature to be 160 °F. This could realistically be raised to 180 °F without damage to the CHE tubes. Figure 9 also shows that increasing the exit water temperature from 160 °F to 180 °F would result in a 21 percent increase in heat recovery and fuel savings. The site personnel are still evaluating the operational implications of increasing exit water to 180 °F and realizing additional savings.

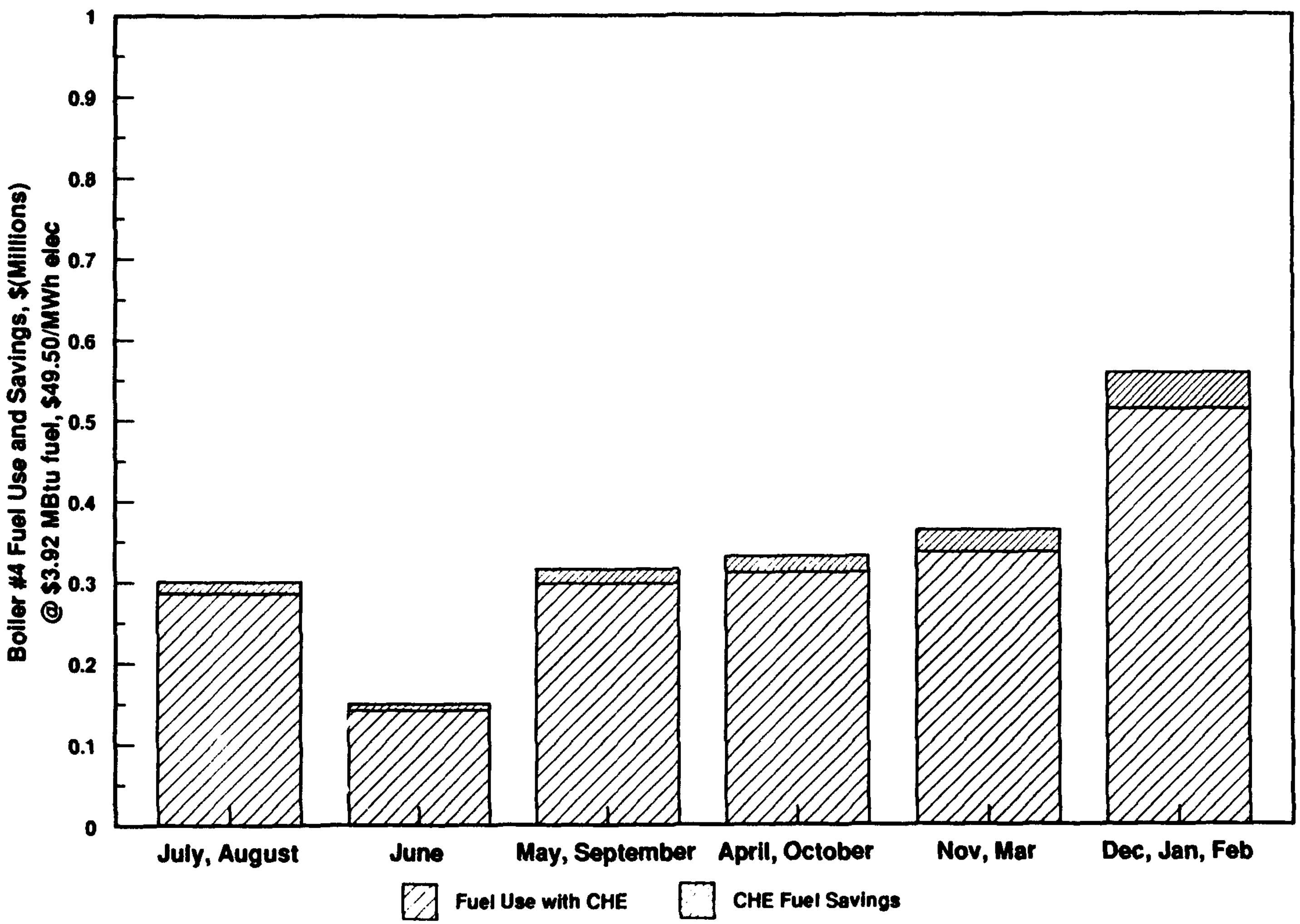

Figure 8. Projected Annual Fuel Use and Savings.

Table 2
Projected Annual Performance

	July Aug	June	Sept May	Apr Oct	Nov Mar	Dec, Jan Feb
Approx. Temp. range °F	75↑	70-74	62-69	50-61	37-49	36↓
Average daily temp.	77.6	73.6	66.5	56.2	38.8	29.7
Days in period	62	30	61	61	61	90
Heat sink: makeup water						
Flow rate, gal/min	44.6	48.6	55.8	66.2	83.7	92.8
Water preheat, °F	95	95	95	95.5	94.7	94.3
Heat recovery, kBtu/hr	2120*	2310	2650	3160	3960	4400
Fuel savings, MBtu/yr	3920*	2080	4850	5820	7340	12,010
Auxiliary energy, MWh/yr	9.4	4.6	9.3	28.9	28.0	42.7
Net fuel savings, $/yr**	14,200*	7500	17,700	20,300	27,300	45,000

*Savings depend on replacement of the BFP turbine with an electrical motor drive as planned for FY91.

**@$3.92/million Btu, $49.5/MWh

Table 3
Original Performance Estimates

	July Aug	June	Sept, May	Apr, Oct	Nov-Mar
Heat sink: makeup water					
Flow rate, gal/min	N/A	50	70	80	90
Makeup water preheat °F	N/A	82	75	91	83
Heat Source: flue gas					
Boiler 4 steam load, lb/hr	0	20,000	30,000	55,000	75,000
Existing efficiency, %	N/A	78.9	80.1	80.2	80.5
Heat recovery, kBtu/hr	0	2100	2600	3600	3700
Annual operation, days/yr	62	30	61	61	151
Annual heat recovery, MBtu	0	1480	3920	5310	13,470
Annual fuel savings, MBtu	0	1875	4900	6620	16,730
Annual savings @ $2.80/MBtu	0	$5250	$13,720	$18,540	$46,800

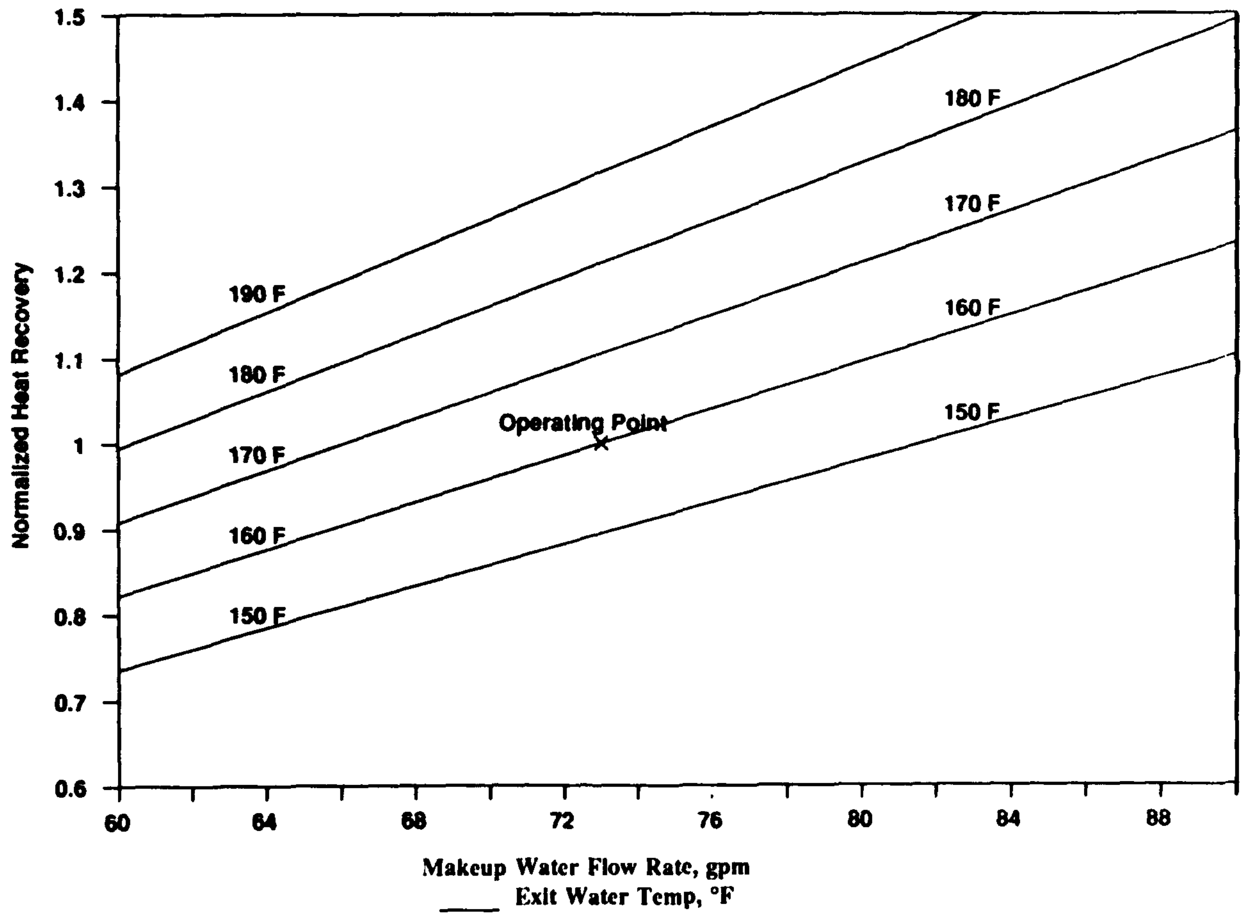

Figure 9. Heat Recovery Variation With Flow Rate, Temperature.

4 CONCLUSIONS AND RECOMMENDATIONS

The demonstration of the Condensing Heat Exchanger system at LCAAP was highly successful. The system has a simple payback of 1.5 years (p 19), with a net annual fuel savings of $132,000 (Table 2). This demonstration has also shown that the CHE system can be installed on a boiler that burns No. 6 fuel oil. The ability to work with fuel cil is consistent with the manufacturer's report that approximately 80 percent of the installed systems are on boilers burning No. 6 fuel oil.

It is important to perform standard "housekeeping" and ensure that the boiler has been tuned-up before installing heat recovery systems. Although a waste heat recovery device will show higher savings when boiler efficiency is low, it is preferable that the fuel not be wasted on the front end.

It is recommended that the procedure for evaluating potential installations of CHE systems be followed as outlined in the Appendix to USACERL Technical Report E-90/09, *Performance of a Condensing Heat Exchanger in Recovering Waste Heat From a Natural Gas-Fired Boiler.*

METRIC CONVERSION TABLE

1 Btu	=	352 g-cal
1 ft	=	0.305m
1 gal	=	3.78L
1 gal/min	=	0.06308L/S
1 in	=	25.4mm
1 lb	=	0.453 kg
1 lb/hr	=	0.126 g/s
1 psi	=	89.300 g/cm^2
1 sq ft	=	0.093m^2
0.55(°F-32)	=	°C

APPENDIX A: ESTIMATING CONDENSING HEAT EXCHANGER APPLICABILITY TO OTHER BOILER PLANTS

Many boiler plants within the U.S. Army could benefit from adding a condensing heat exchanger waste heat recovery system. Boilers without economizers and little or no condensate return offer the greatest potential for heat recovery. Evaluation of a potential condensing heat exchanger application follows a simple four-step process:

1. Identify heat sources

2. Identify heat sinks

3. Match loads

4. Calculate savings and simple payback.

The procedure outlined below gives a preliminary evaluation of whether a potential application is worth further consideration. If so, a more detailed analysis should be performed.

Identify Heat Sources

When fuel is burned in a boiler, a major part of the heat produced is used to generate steam, and a smaller part is lost by conduction through the boiler walls, or is exhausted in the flue gases. The boiler efficiency varies according to the steam demand and allows one to determine how much of the supplied fuel is converted to steam. For a first pass analysis, losses through the boiler walls can be neglected and the heat losses quantified as whatever is not converted into steam. Although this will overstate the amount of heat available, the result is still useful in determining whether further analysis should occur. If the results of this analysis indicate a cost effective project, a more detailed analysis may be conducted.

For example, the load profile of a boiler has been divided into winter and summer bins of similar boiler efficiences (Table A1). For instance, a boiler might normally operate at two firing rates, with a summer average boiler efficiency of 80 percent and a winter efficiency of 76 percent. The energy available for each bin (Q_H) is a function of fuel use rate (F_{in}), boiler efficiency (η_B), and operating hours (ΔT):

$$Q_H = F_{in}\Delta T(1 - \eta_B) \qquad \text{[Eq A1]}$$

Table A1 shows that for this example problem, the energy available in the winter bin is 19,443 MBtu and in the summer bin is 7647 MBtu. This example assumes that only the heat from one boiler would be recovered, but it is often the case that flue gases from two or more boilers could feasibly be ducted to the same condensing heat exchanger.

Identify Heat Sinks

It is important to first identify liquid streams that could be heated with a condensing heat exchanger. In the case of a boiler with limited or no condensate return, the makeup feedwater stream is a good candidate. For cost efficiency, consider flows that pass through the boiler room or adjacent buildings

Table A1

Heat Source Determination

Winter:	
fuel use rate, kBtu/h	22,256
boiler efficiecy (%)	80
operating hours, h	4368
energy available, MBtu	$= \frac{22,256}{1000} \times .2 \times 4368$
	= 19,443
Summer:	
fuel use rete, kBtu/h	7809
boiler efficiency, (%)	76
operating hours, h	4080
energy available, MBtu	$= \frac{7809}{1000} \times .24 \times 4080$
	= 7647
Total Energy Available, MBtu	= 27,090

first. Note the cold temperature (T_{in}), the hot temperature (T_{out}), and the mass flow rate (m in pounds per hour) for each stream. The energy required in each bin (Q_L) is:

$$Q_L = mc(T_{out} - T_{in}) \qquad \text{[Eq A]}$$

where c = the heat capacity of water (1 Btu/lb_m- deg F).

Table A2 shows the energy requirement to preheat makeup feedwater for the boiler used as a heat source in A1.

Match Loads

The most important factor affecting the ability of the heat sink to use heat provided by the heat source is that the heat source must be available in a usable form. To use an obvious example, the temperature of the heat source must be higher than T_{out} required by the heat source, or only a portion of the heat source may be used. Also, the lower T_{out} is, the more effectively heat can be transferred to the heat sink. This fact explains why it is better to heat makeup feedwater, which usually has a T_{in} equal to the ground water temperature, than to heat condensate return, which is considerably hotter. Assuming that the above prerequisites are met, the maximum energy savings for each bin are:

$$Q_{saved} = \text{the lesser of } Q_H \text{ or } Q_L \qquad \text{[Eq A3]}$$

Table A3 gives the results for the example problem. The annual energy savings are found by summing the energy savings for each bin.

Table A2

Heat Sink Determination

Winter:		
flow rate, lb/h - m	12,000	
Source temperature, F-T_{out}	180	
Sink temperature, F-T_{in}	60	
operating hours, h	4368	
energy need, MBtu		6290
Summer:		
flow rate, lb/h - m	4000	
Source temperature, F - T_{out}	180	
Sink temperature, F - T_{in}	65	
operating hours, h	4080	
energy need, MBtu		1877
Total energy Requirements, MBtu		8167

Calculate Savings and Simple Payback

Cost savings are found by multiplying the quantity of fuel that would have been burned to produce Q_{saved} (taking the annual weighted average boiler efficiency into account) by the cost of the fuel:

$$\text{Savings} = \text{Fuel Cost} \times Q_{saved}/\eta_B \qquad \text{[Eq A4]}$$

Simple payback (S) is found by dividing the initial cost of the system by the annual cost savings:

$$S = (\text{system cost})/\text{Savings} \qquad \text{[Eq A5]}$$

The cost of equipment and installation is site-specific. However, some factors that affect installation costs are:

1. The need for a holding tank and recirculation loop to accommodate load mismatching or batch flows.

2. Extensive ductwork necessary to connect more than one boiler.

3. Additional (water-water) heat exchangers to accommodate hot water temperature needs of different streams or for segregating softened water from city water.

4. Physical space accessibility; can the condensing heat exchanger be installed on the boiler roof? In a building addition? Is structural work required to place the unit in the boiler room?

Table A3

Energy Savings Determination

Energy Transfer	
Winter, MBtu minimum of [6290, 19443]	6290
Summer, MBtu minimum of [1877, 7647]	1877
Total Energy Requirements, MBtu	8167

Is Further Analysis Justified?

Generally, if the condensing heat exchanger application being considered has a simple payback of less than 5 years, a more detailed analysis is highly recommended and the system has a high probability of providing a quick return on investment. If the simple payback is between 5 and 10 years, other factors such as the time value of money, fuel escalation rates, operating and maintenance costs, and salvage value become more important. The Life Cycle Cost in Design (LCCID) program is the recommended method of carrying out this analysis. It is available through the BLAST support office at the following address:

BLAST Support Office
144 Mechanical Engineering Building
1206 West Green Street
Urbana, IL 61801

Other Examples

In the example given, only one boiler plant is serving as a heat source; the heat sink is the cold makeup water serving the same boiler. Boiler loads are lighter in the summer, so less heat is available for recovery. Since less steam is required, less makeup water must be heated. Ground water temperature is also higher in the summer, requiring less preheating before injection as makeup feedwater. In the winter, the opposite is true, since high steam loads require large amounts of makeup feedwater. The loads are well matched not only throughout the year, but also daily and hourly.

It is possible and often practical for a heat exchanger to recover waste heat from the flue gas of several boilers and to use this heat to preheat not only makeup water, but also laundry water, domestic water, and/or process water. Condensing heat exchanger applications have also included preheating combustion air, although this is less common. Table A4 gives sample calculations for four hypothetical cases. Cases 1 and 2 are straightforward. Case 3 has an insufficient load to effectively use the heat available from the condensing heat exchanger. Case 4 depicts a system that uses the heat from one boiler to preheat feedwater for four boilers.

Table A4

Cost and Savings Expected for Hypothetical Applications

Case	1	2	3	4
Description	20% Condensate Return Makeup Water (1 boiler)	Heat Domestic Hot Water (1 boiler)	80% Condensate Return (1 boiler)	One Boiler Heats Feedwater for Four Boilers With 80% Condensate Return
<u>Heat Sink</u>				
Winter:				
flow rate, lb/h	12,000	33000	3000	12000
hot temp, °F	180	120	180	180
cold temp, °F	60	60	60	60
operating hours, h	4368	4368	4368	4368
energy need, MBtu	6290	8650	1570	6290
Summer:				
flow rate, lb/h	4000	33000	1000	4000
hot temp, °F	180	120	180	180
cold temp, °F	65	60	65	65
operating hours, h	4080	4368	4080	4080
energy need, MBtu	1880	8650	470	1880
Total	8170	17300	2040	8170
<u>Heat Source</u>				
Winter:				
fuel use rate, kBtu/h	22,256	22,256	22,256	22,256
operating hours, h	4368	4368	4368	4368
boiler efficiency, %	80	80	80	80
energy available, MBtu	19440	19,440	19,440	19,440
Summer Operation:				
fuel use rate, kBtu/h	7810	7810	7810	7810
operating hours, h	4080	4080	4080	4080
boiler efficiency, %	76	76	76	76
energy available, MBtu	7467	7647	7647	7647
Total Energy Available, MBtu	27090	27,090	27,090	27,090
Annual Energy Savings, MBtu	8170	17,300	2,040	8170
Annual Average Boiler Efficiency	79	78	79	79
Annual Savings, $ @2.50/MBtu	25,854	55,949	6457	25,854
Approximate Cost	70,000	75,000	70,000	80,000
Simple Payback	2.7	1.4	10.8	3.1

APPENDIX B: CONDENSING HEAT EXCHANGER DESIGN AND PERFORMANCE SPECIFICATIONS

Condensing Heat Exchanger Physical Design Specifications

Model number	240-60 DW5
Tube material	Copper Alloy 706
Tube specification	ASTM-B111
Tube arrangement per module	8 x 30
Number of modules	5
Tube length	60 in.
Tube size (O.D.)	1.125 in.
Tube wall thickness	0.035 in.
Design pressure	100 psig @ 200 °F water temperature
Test pressure	200 psig @ 100 °F
Design temperature	200 °F (water side), 500 °F (gas side)
Shell casing material	10 gauge carbon steel
Teflon covering	0.015 in. (on tube O.D.), 0.060 in. (on gas side of shell)
Heat exchanger height	12.0 ft
Heat exchanger depth	5.3 ft
Heat exchanger width	4.8 ft
Dry weight	6772 lb
Flooded weight	9017 lb
Heat exchanger surface area	1590 sq ft
Number of water manifold inlets/exits	15 connections
Minimum allowable waterflow	22.5 gpm
Maximum waterflow	125 gpm @ 20 psi

Performance Under Nominal Load Conditions for Test Period

	Value	Source
Heat sink:		
waterflow through HX, gpm	73	Data average
water inlet temperature, °F	65	Calculated
water exit temperature, °F	160	Estimated from data
Heat Source:		
flue gas available, lb/hr	50,185	Calculated from data
flue gas flow through HX, lb/hr	40,150	Estimated
flue gas inlet Temperature, °F	365	Data average
flue gas exit temperature, °F	125	Estimated from data
steamload, lb/hr -		
total plant	69,000	Data average
corresponding, Boiler 4	48,200	Data average
minimum, Boiler 4	32,000	Calculated

Heat exchanged:		
sensible heat recovery, kBtu/hr	2560	Estimated
latent heat recovery, kBtu/hr	940	Estimated
total heat recovery, kBtu/hr	3500	Data average
Site parameters:		
existing thermal efficiency, %	82.5	Data average
fuel cost, $/million Btu	$3.92	Site supplied
hours of operation	3336	Test period
Result:		
new thermal efficiency, percent	88.7	Calculated
fuel savings, kBtu/hr	4220	Calculated
fuel savings, $	55,000	Calculated

APPENDIX C:

FUEL SAVINGS CALCULATION

Consider the boiler system shown in Figure C1.

The CHE is used to preheat makeup water. Therefore, to analyze fuel savings you need only consider the affect of increasing the temperature or enthalpy of the makeup water, h_m. This will reduce the steam to the deaerator, d, and result in reduced water flow through the boiler and reduced fuel consumption.

Constructing mass and energy balances around the system you find:

<u>Deaerator</u>

$$\textit{mass balance, } m+c+d=f \qquad \text{[Eq C1]}$$

$$\textit{energy balance, } mh_m + ch_c + dh_d = fh_f \qquad \text{[Eq C2]}$$

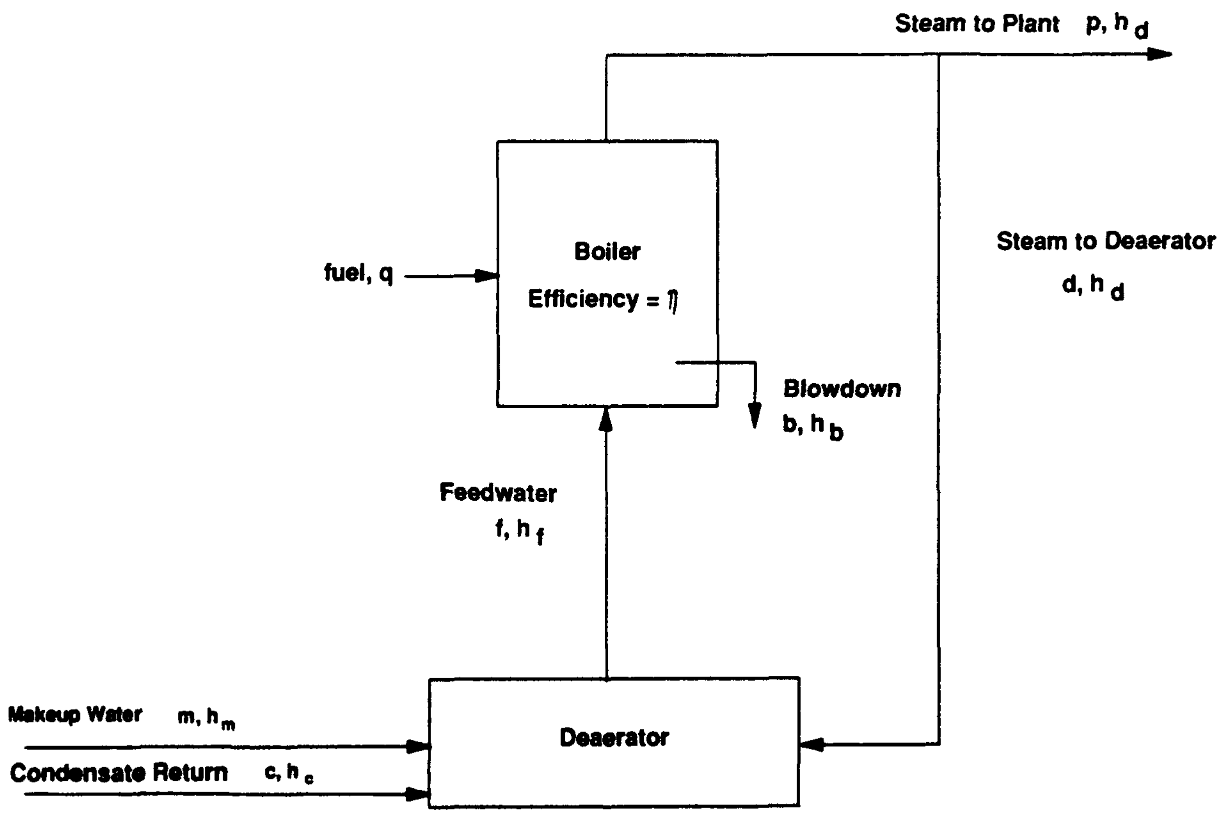

Figure C1. Example Boiler System.

Boiler

$$mass\ balance,\ f=b+p+d \quad \text{[Eq C3]}$$

where b = xf

$$energy\ balance,\ fh_f+\eta q=bh_b+ph_d+dh_d \quad \text{[Eq C4]}$$

After some algebra you can show makeup water, m, as a function of steam to plant, p, and condensate return, c:

$$m=\frac{p+c\left[x\frac{(h_d-h_c)}{(h_d-h_f)}-1\right]}{\left[1-x\frac{(h_d-h_m)}{(h_d-h_f)}\right]} \quad \text{[Eq C5]}$$

Given h_d = 1195.55 Btu/lb
h_c = 100 Btu/lb
h_f = 190.25 Btu/lb
h_b = 338.65 Btu/lb
h_{m1} = 33 Btu/lb
h_{m2} = 128 Btu/lb

Then,

$$m_1(\text{withoutCHE})=\frac{p+c(1.09x-1)}{(1-1.156x)} \quad \text{[Eq C6]}$$

$$m_2(\text{withCHE})=\frac{p+c(1.09x-1)}{(1-1.062x)} \quad \text{[Eq C7]}$$

Assuming blowdown is at 11 percent (x = 0.11)

$$m_1=\frac{(p-0.88c)}{0.873} \quad \text{[Eq C8]}$$

$$m_2=\frac{(p-0.88c)}{0.883} \quad \text{[Eq C9]}$$

$$\Delta m = m_2 - m_1 = m_2\left[1 - \frac{0.833}{0.873}\right] = 0.0115 m_2 \qquad \text{[Eq C10]}$$

And,

$$\Delta d = \frac{(h_f - h_{ml})\Delta m - m_2 \Delta h_m}{h_d - h_f} = \frac{157.25\Delta m - m_2 \Delta h_m}{1005.3} \qquad \text{[Eq C11]}$$

Finally, assuming η is constant over this small range,

$$-\Delta q = \frac{1}{\eta}[(h_f - xh_b)\Delta m + (h_f - xh_b - h_d)\Delta d] = \frac{1}{\eta}[153\Delta m - 1042.5\Delta d] \qquad \text{[Eq C12]}$$

Now, recognizing that fuel savings, FS = $-\Delta q$, heat recovery HR = $m_2 \Delta h_m$, and substituting equation C10 for Δm, we can express fuel savings in terms of known parameters:

$$FS = -\Delta q = \frac{1}{\eta}[1.037HR - 0.116m_2] \qquad \text{[Eq C13]}$$

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