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Economics of Feedwater Heater Replacement

As feedwater heaters age, performance deteriorates and leaks invariably occur. In order to keep the heater functioning properly, and to avoid the possibility of water backing into the turbine and causing damage, the leaking tubes are plugged. Usually, the initially plugged tubes cause small, if any, deterioration of performance. Eventually, the number of plugged tubes significantly affects the overall cycle efficiency. This paper presents a straightforward method for calculating the economical time for repair or replacement, without the need for extensive heat balance calculations or special rules of thumb. While the analysis presented here, based on the useful energy concept, is used to solve an operating problem, the same methods can be readily applied at the design stage, and can be used on any other component in the power cycle as well.

Introduction

The power plant engineer is often faced with the problems of assessing the change in operating costs due to the deterioration of performance of individual pieces of equipment in the power cycle and of predicting the effect upon heat rate due to changes of equipment or operating procedures. When presented with such tasks the engineer has a number of techniques from which to choose to perform his evaluation:

(*a*) He can perform an energy balance (first law analysis) upon the piece of equipment, or system, in question—a technique that often inaccurately predicts over-all changes in unit efficiency and leads to erroneous conclusions.

(*b*) The engineer can perform an energy balance (first law analysis) on the total power cycle—an arduous task and one that is often impossible to perform due to the lack of unit operating data at other than design conditions. Even if done with a sophisticated computer program, considerable engineering time is involved, and the confidence level in the results is often in question.

(*c*) He can use "rules-of-thumb" that have been propagated in various technical articles and textbooks—use of which often leads to questionable results due to the inaccuracies of applying generalized "rules" to a specific situation.

(*d*) If the system with the deteriorated equipment is in operation, the engineer can request a heat rate (or unit efficiency) test. By measuring the fuel input, as well as the electrical output, the overall unit efficiency can be determined. Reliable interpretation of the results from such a test, however, is extremely difficult if not impossible. What portion of increased heat rate is attributable to the equipment in question and what portion is due to other system components and variables?

(*e*) Finally, he could employ a useful energy analysis, based on the second law of thermodynamics, which can be used to evaluate the quantity of (useful) energy consumed by the piece of equipment of interest. In a second law analysis, the amount of useful energy consumed by any process can be evaluated, *as well as* the unit cost of that energy; in turn, the costs associated with the process can be found.

While the techniques associated with a second law analysis are straightforward, they have seldom been used in the past in the power industry. This has been a result of inhibitions associated with the concept of entropy and the second law. There is no question that the second law of thermodynamics will correctly predict relative efficiencies and the associated operating costs of any power plant system, and that it alone can be used: (i) to evaluate the efficiency of each piece of equipment and the processes therein [1–9] and (ii) to determine the monetary value (including capital cost amortization) of the (useful) energy at each juncture of the power plant [10, 11].

Importantly, to demonstrate the misleading answers that an energy balance can provide, consider the following simple example:

Suppose one were to expand steam from p_1 = 1000 psig and T_1 = 1000°F through a pressure reducing valve, to an end pressure p_2 = 100 psig. Since no work is accomplished by the process, and the heat losses are minimal, the energy carried via the steam leaving the pressure reducing station is equal to that which entered; there is *no*

Contributed by the Power Division of THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS and presented at the IEEE-ASME Joint Power Generation Conference, Buffalo, N. Y., September 19–22, 1976. Manuscript received at ASME Headquarters June 23, 1976, Paper No. 76-JPGC-Pwr-7.

loss of *energy*. The useful energy attributable to the high temperature, high pressure steam (useful energy which could ideally be converted into shaft work or any other form of useful energy) is:[1]

$$a_1 = (h_1 - h_0) - T_0(s_1 - s_0)$$

where the subscript "0" denotes the ambient conditions at atmospheric pressure and temperature, assumed to be 14.7 psia and 510°F. Then, the useful energy at point 1 is:

$$a_1 = (1505.4 - 18.10) - 510(1.6530 - 0.036) = 662.64 \text{ Btu/lb}$$

while the useful energy at point 2 is:

$$a_2 = (1505.4 - 18.10) - 510(1.885 - 0.036) = 544.31 \text{ Btu/lb}$$

Therefore we can conclude not only the rather obvious qualitative point, that the ability to produce work is reduced by throttling the steam, but we also obtain a quantitative measure of the reduction. The consumption of the useful energy by the process is the difference between the useful energies at point 1 and 2:

$$a_{\text{consumption}} = a_1 - a_2 = 662.64 - 544.31 = 118.31 \text{ Btu/lb}$$

Thus in order to accomplish the desired pressure reduction with simple throttling, 118.31 Btu's of (useful) energy had to be consumed for each pound of steam throttled. As is commonly done, we can define the proportion of (useful) energy output to input as the 2nd-law efficiency[2] of the process:

$$\eta_{\text{II}} = A_{\text{product}}/A_{\text{input}}$$

For the throttling process at hand,

$$\eta_{\text{II}} = 544.31/662.64 = 0.821$$

or only 82.1 percent of the initial useful energy is available, say to produce work, after passing through the pressure reducing station.

Any energy that a substance contains when it is at its *dead state,* in equilibrium with its ambient environment, is unavailable and cannot be used to derive net work. And conversely when a substance is not at equilibrium with its environment, it contains the potential to cause change, such as to produce *useful* work. The commodity here being called useful energy[3] is the correct quantitative measure of this potential to cause change; this potential is called the useful energy (and is synonymous with what the layman calls "energy"). The essence of the second law is that useful energy must be consumed (used up, destroyed) in order to accomplish any *real* process—in order to make any change proceed. Useful energy cannot be produced, but only consumed; in the hypothetical limit of *ideal*[4] processes no useful energy is consumed.

Energy converters and systems take useful energy in one form (e.g., chemical form, in coal) and convert a portion of it to another form (e.g., electrical); the difference is literally consumed in the system, "driving" the various processes.[5] Of course, the cost of the product (output useful energy) from a converter or system is a consequence of the fuel (input useful energy) cost, the capital costs associated with the equipment, along with other variable and fixed costs. The greater η_{II} is, the lower is the fuel cost; generally, though, the capital cost is then greater. Thus, for a simple system with one product and one fuel we can write that the annual cost of product equals the annual fuel costs, plus the annualized capital and other costs: (dollars$_p$/yr) = (dollars$_F$/yr) + (dollars$_c$/yr). Expressing (dollars$_F$/yr) as the product of the annual fuel consumption (A_F, Btu of useful energy per year) with the unit cost of fuel (c_F, dollars/Btu), (dollars$_p$/yr) = $c_F A_F$ + (dollars$_c$/yr). In turn, the unit cost of the product provided by the system is:

$$c_p = \frac{\text{dollars}_p/\text{yr}}{A_p,\ \text{Btu/yr}} = c_F \frac{A_F}{A_p} + \frac{(\text{dollars}_c/\text{yr})}{A_p}$$

Thus, since $\eta_{\text{II}} = A_p/A_F$,

$$c_p = c_F/\eta_{\text{II}} + \text{dollars}_{c,\text{annual}}/A_p \tag{1}$$

The first term on the right reflects fuel costs; the second equals the annual capital (and other) costs per unit of system capacity. Normally, to decrease the first requires an increase in the second, and, of course, the aim is to make the investment which minimizes the total. Equations like (1) can be developed [10, 11] to determine the unit cost of useful energy at the various junctures between components of an energy system. The key to the results presented in this paper is such development of the relevant unit costs for the problem at hand.

Scope, and Problem Description

Second law techniques are here applied to the problem of determining when to replace feedwater heaters. This analysis is performed as a hypothetical engineering case, as a test of a decision which had recently been made in a real case under consideration by Wisconsin Electric Power Company.

Modern steam power plants employ feedwater heaters to raise the temperature of the feedwater entering the boiler. Steam is extracted from the turbines at various "bleed points," and is commonly (closed heaters) condensed over tube bundles inside which the boiler feedwater runs; Fig. 1.

Feedwater heaters increase plant efficiency by increasing the average temperature at which heat is supplied to the cycle H_2O from products of combustion [6, Articles 15.1–6]; that is, inasmuch as useful energy consumption for driving heat transfer processes increases with $[T_{\text{source}} - T_{\text{recipient}}]$, feedwater heaters increase plant efficiency by decreasing this average ΔT for heat transfer to H_2O [8].

The number of feedwater heaters in the cycle is commonly based

[1] See any of references [1–9] or many of the standard thermodynamics textbooks for the development of the mathematical expressions for useful energy. References [8, 9] give palatable explanations of useful energy and the second law, as well as straightforward developments of the expressions.

[2] This is actually the *true* efficiency of the process, but to avoid confusion with the energy efficiency the adjective "2nd-law" is used; for a long time [1, 2] the term "effectiveness" has been employed for η_{II}, but now there is the likelihood of confusing it with heat exchanger "effectiveness," which although it is often *called* a second-law efficiency, is different from η_{II}.

[3] Many other names have been employed, besides useful energy; e.g., available energy, availability, available work, exergy, essergy, potential energy.

[4] So-called "reversible" processes are ideal.

[5] It is true that a *part* of the difference might not be a consequence of consumptions, but of losses in effluents. The losses are generally small relative to the consumptions, contrary to misconceptions which prevail as a result of first-law analyses [8, 9].

Nomenclature

a = specific useful energy, Btu/lb (J/g)
A = useful energy flow rate, Btu/hr (J/s)
c = unit cost, dollars/MBtu (dollars/10^6J)
h = specific enthalpy, Btu/lb (J/g)
m = mass flow rate, lbs/hr (g/s)
s = specific entropy, Btu/lb-° R (J/g-K)
T = absolute temperature, ° R (K)
η_{I} = first law efficiency
η_{II} = second law efficiency

Subscripts

B = bleeder
C = capital
F = fuel
P = product
RH = reheat
S = shaft
T = throttle
t = turbine
0 = dead state, ambient conditions

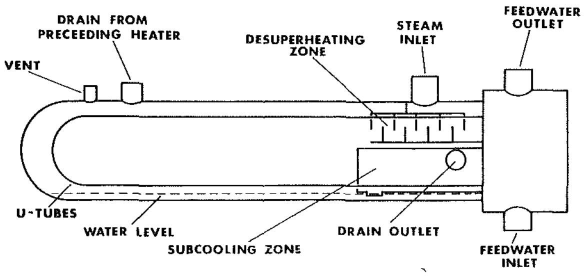

Fig. 1 Typical feedwater heater

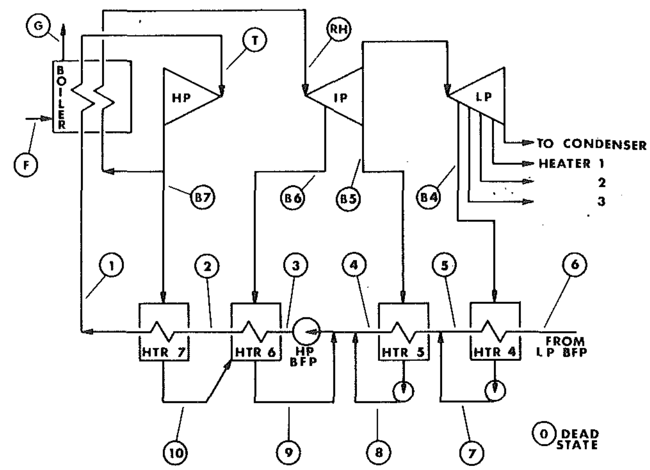

Fig. 2. Schematic of typical unit

upon the economic trade-off between the first cost of the unit and the expected annual operating savings due to the increase in unit efficiency. In practice, it is also limited by the maximum number of bleeder stages which the turbine manufacturer supplies with a given size turbine.

As feedwater heaters age, there is film build-up inside the tubes, "exfoliation" on the outside tube surfaces, and leaks invariably occur. Normally, leaks occur infrequently during the first decade of the heater's life with the frequency increasing rapidly as the mean life of the tubes is approached. In order to return the heater to functional operation, and to avoid the possibility of water backing into the turbine and cuasing damage, a leaking heater must be taken out of service while the leaking tubes are plugged.

If the heater is conservatively designed, as is usually the case, the initially plugged tubes cause small, if any deterioration of performance. Eventually, however, *film buildup, exfoliation and plugged* tubes increase to the point that the heater can no longer operate near design conditions. As the feedwater heater efficiency drops off it affects the overall cycle efficiency, which causes an increase in operating costs, and at some stage the heater should be replaced.

The following analysis deals with the techniques of evaluating when a feedwater heater should be replaced.

The cycle studied in the ensuing analysis is a fairly typical one, with seven stages of extraction to the feedwater heaters. This Unit is shown schematically in Fig. 2. Table 1 presents the temperature and enthalpy of water at various points in the feedwater system; Case A represents the properties at design conditions, while Cases B and C represent deteriorated conditions to be described presently. Table 2 presents steam properties and flow rates. Except for the boiler feedwater flow rate, $m_1 = m_T$, which is 1,869,000 lb/hr for the Unit at full load, the other flow rates in Table 2 were calculated with energy balances, using the enthalpies listed in Tables 1 and 2. The additional boiler fuel flow shown for Case C is the increase needed to take the boiler feedwater from $T_{1,C}$ = 460°F to the normal feedwater temperature, $T_{1,A}$ = 471.7°F.

A complete analysis of useful energy flows, consumptions and losses for this Unit under design conditions has been presented earlier [8], and the results are employed in the economic analysis to follow, here.

Case B is intended to represent the situation when, after years of

Table 1 Feedwater and drain temperatures and enthalpies

	Temperature - °F (°C)			Enthalpy - BTU/LB (J/g)		
Point	CASE A	CASE B	CASE C	CASE A	CASE B	CASE C
1	471.7 (244.3)		460.0 (237.8)	455.6 (1059.7)		442.9 (1030.2)
2	385.3 (196.3)		370.0 (187.8)	362.8 (843.9)		347.0 (807.1)
3	325.4 (162.9)	321.0 (160.6)	285.0 (140.6)	300.9 (699.9)	296.4 (689.4)	259.9 (604.5)
4	316.6 (158.1)	311.6 (155.3)	273.7 (134.3)	287.0 (667.6)	282.3 (655.6)	242.9 (565.0)
5	273.5 (134.2)			242.8 (564.7)		
6	200.0 (93.3)			168.4 (391.7)		
7	275.5 (135.3)			244.5 (568.7)		
8	319.6 (159.8)			289.9 (674.3)		
9	335.4 (168.6)			306.5 (712.9)		
10	395.3 (201.8)			370.2 (861.1)		

Note: Data for points whose properties did not change from design conditions was omitted for clarity. Point refers to the point in the cycle as defined by Figure 2.

Table 2 Properties* and flow rates of useful energy supplies

Point[+]	Pressure Psia (kPa)	Temperature °F (°C)	Enthalpy BTU/LB (J/g)	Entropy BTU/LB °F (J/g °K)	Flow Rate LB/HR (g/s) CASE A	LB/HR (g/s) CASE B	LB/HR (g/s) CASE C
H_2O Dead State	14.7 (101.4)	50.4 (10.2)	18.5 (43.0)	.0369 (.1545)			
B7	524.6 (3617)	654.8 (345.9)	1329.9 (3093.3)	1.5832 (6.728)	180,890 (22,800)	180,890 (22,800)	189,500 (23,900)
B6	221.3 (1526)	798.3 (425.7)	1423.8 (3311.7)	1.7539 (7.343)	93,200 (11,738)	100,800 (12,700)	136,100 (17,100)
B5	93.8 (647)	607.7 (319.8)	1331.1 (3096.1)	1.7696 (7.409)	64,788 (8,200)	57,900 (7,300)	0 (0)
B4	49.8 (343)	475.1 (246.2)	1271.9 (2958.4)	1.7766 (7.438)	103,300 (13,000)	103,300 (13,000)	106,700 (13,400)
RH	482.6 (3,227)	1000 (538)	1520.1 (3535.7)	1.742 (7.293)	1,640,200 (206,700)	1,640,200 (206,700)	1,631,600 (205,600)
T	2400 (16,547)	1050 (566)	1493.8 (3474.5)	1.555 (6.510)	1,869,000 (234,700)	1,869,000 (234,700)	1,869,000 (234,700)
F	14.7 (101.4)	50.4 (10.2)	11,875 (27,620)	-1.0445 (-4.3731)			+2,173 (+ 273)

*Reference states: For H_2O, liquid at 32°F and 1 atm. For fuel, components at complete equilibrium in the ambient environment at 510°R and 1 atm.

[+]Point refers to the point in the cycle as defined by Figure 2.

service, the heater supplied by steam from bleeder B5 has had say twenty percent of its tubes plugged. The terminal temperature difference (TTD—the difference between saturated steam temperature and feedwater outlet temperature) can be expected to decrease by approximately five degrees (°F). If heater number 6, supplied by B6, is in good condition it would nearly pick up the load which heater 5 failed to carry. These are the circumstances assumed for Case B, on Table 1.

At some stage, the deterioration of performance becomes so great that the heater should be taken out of service in order to either (i) replace it with a new heater, or (ii) retube the heater, which generally involves more down-time than replacement. Case C portrays the situation when heater 5 is out of service, causing greater upset to the feedwater circuit than Case B. Notably, the temperature of the feedwater to the economizer section of the boiler is lower.

The economic analysis to follow depends upon the evaluation of the various useful energy supplies for feedwater heating and, in turn, the costs associated with those supplies. In particular, the costs of interest, for each case, are those required to take the feedwater from the conditions at the inlet to heater number 4 to the normal temperature of feedwater entering the boiler.

Useful Energy Supplies

For example, consider the supply of useful energy from $B7$; $A_{B7} = m_{B7}a_{B7}$. For Case A,

$$A_{B7} = m_{B7}[h_{B7} - h_0 - T_0(s_{B7} - s_0)]$$

$$= 180{,}890[1329.9 - 18.5 - 510(1.5832 - 0.0369)]$$

$$= 94{,}565{,}000 \text{ Btu/hr}$$

The values for m_{B7}, h_{B7}, s_{B7}, h_0 and s_0 are from Table 2. The useful energy required from each bleed source was calculated in exactly this manner, and the results are listed in Table 3. One more useful energy supply needs to be considered.

Under the conditions of Case C, when heater 5 is out of service, the temperature of the feedwater (460°F) is below normal, and additional useful energy (fuel) must be supplied to the boiler to bring the feedwater up to normal temperature (471.7°F). The corresponding energy requirement is 1,869,000(455.6 − 442.9) = 23,736,300 Btu/hr. With a boiler efficiency $\eta_I = 0.92$, additional fuel energy is required at the rate 25,800,326 Btu/hr. Assuming a fuel with a heating value of 11,875

Table 3 Useful energy requirements and costs

Useful Energy Source	Useful Energy Requirements BTU/HR (J/s) CASE A	BTU/HR (J/s) CASE B	BTU/HR (J/s) CASE C	Unit Cost of Useful Energy $/10^6 BTU	Cost of Useful Energy Requirements $/HR CASE A	$/HR CASE B	$/HR CASE C
B4	37,818,000 (11,083,000)	37,818,000 (11,083,000)	39,069,000 (11,450,000)	1.270	48.028	48.028	49.618
B5	27,787,000 (8,144,000)	24,824,000 (7,275,000)	-	1.354	37.624	33.611	-
B6	49,337,000 (14,459,000)	53,365,000 (15,640,000)	72,080,000 (21,124,000)	1.459	71.983	77.860	105.165
B7	94,565,000 (27,714,000)	94,565,000 (27,714,000)	99,050,000 (29,028,000)	1.443	136.457	136.457	142.929
F Increase	-	-	26,945,000 (7,897,000)	0.800	-	-	21.556
Totals	209,507,000 (61,400,000)	210,573,000 (61,712,000)	231,620,000 (67,880,000)		294.093	295.957	319.267

Btu/lb, an additional 2173 lb/hr of fuel must be supplied, as shown in Table 2.

Inasmuch as the useful energy content of hydrocarbon fuels is close in value to their heating value [5, 12], 25,800,326 Btu/hr is essentially equal to the additional fuel useful energy supply. However, if a more precise evaluation is desired, for fuels of known composition methods like those of [4, pp. 393–395] or [5, pp. 395–397] can be employed to evaluate fuel useful energy content. Application of these methods to the fuel at hand gives[6] $a = [h - h_0 - T_0(s - s_0)] = 11875 + 510(1.044) = 12400$ Btu/lb. Therefore, the additional supply of useful energy with fuel, for Case C, is

$$A_{f,\text{additional}} = (2173)(12400) = 26{,}945{,}000 \text{ Btu/hr}$$

Next, the cost of each useful energy supply will be evaluated.

Unit Costs of Useful Energy

Consider first the value of useful energy at a bleed point like $B7$. The value of the steam leaving the turbine, $(\text{dollars/hr})_B$, equals that of the steam supplied to it $(\text{dollars/hr})_T$ less the value of useful energy garnered from the steam by the turbine; that is, less the value of the useful energy output from the turbine shaft. In other words, the total "fuel" cost attributable to the turbine's two products equals the investment in "fuel," throttle steam, needed to supply the products:

$$[\text{dollars/hr}]_B + [\text{dollars/hr}]_{\text{shaft}} = [\text{dollars/hr}]_T$$

Or,

$$c_B A_B + c_s A_s = c_T A_T$$

No term has been included for amortization of the turbine, since the capital is already sunk. The second law efficiency of the turbine is defined by $\eta_{\text{II,turbine}} = A_s/[A_T - A_B]$. Hence,

$$c_B A_B = c_T A_T - c_s[A_T - A_B]\eta_{\text{II,turbine}}$$

Then,

$$c_B = \frac{A_T}{A_B} c_T - \frac{[A_T - A_B]\eta_{\text{II},t}}{A_B} c_s \tag{2a}$$

Dividing numerators and denominators by the mass flow rate of steam through the turbine,

$$c_B = \frac{a_T}{a_B} c_T - \frac{a_T - a_B}{a_B} \eta_{\text{II},t}\, c_s \tag{2b}$$

If the unit cost of useful energy in throttle steam and that in the shaft output were known, c_B could then be calculated from the property data in Table 2 and $\eta_{\text{II},t}$ from [8].

For the case of c_{B7}, the value c_T of interest is that of the useful energy in throttle steam to the high pressure turbine. That useful energy was acquired in the boiler, at the expense of useful energy in the fuel; since boiler capital is sunk, the hourly fuel cost attributable to throttle steam, $c_T A_T$, equals the hourly expenditure on fuel for producing the high-pressure steam:

$$c_T A_T = c_F A_{F,HP}$$

Then,

$$c_T = c_F \frac{A_{F,HP}}{A_T} = c_F/\eta_{\text{II},HP \text{ boiler}}$$

where the definition of the second law efficiency of the boiler's high pressure section has been invoked. With $c_F = 0.80$ dollars/10^6 Btu, and with $\eta_{\text{II,boiler}} = 0.514$ from [8],[7]

$$c_T = 0.8/0.514 = 1.556 \text{ dollars}/10^6 \text{ Btu}$$

To obtain c_s notice that the useful energy delivered to the generator via the shaft can also be expressed in terms of the unit cost of fuel useful energy, as follows. The only useful output of the power cycle is the useful energy delivered to the generator; its total hourly fuel cost is equal to that of the fuel consumed to produce it: $c_s A_s = c_F A_F$. Then, with $\eta_{\text{II,cycle}} = A_s/A_F$,

$$c_s = c_F/\eta_{\text{II,cycle}}$$

and

$$c_s = 0.8/0.391 = \$2.046/10^6 \text{ Btu}$$

where $\eta_{\text{II}} = 0.391$ is from [8].

From Table 2,

$$a_T = h_T - h_0 - T_0(s_T - s_0) = 1493.8 - 18.5 - 510(1.55 - 0.037)$$
$$= 704.069 \text{ Btu/lb}$$

$$a_{B7} = 1329.9 - 18.5 - 510(1.5832 - 0.0369) = 521.869 \text{ Btu/lb}$$

Substituting these values for a_T and a_{B7} into equation (2b), along with the above values for c_T and c_s, as well as $\eta_{\text{II}} = 0.92$ for the high pressure turbine [8],

$$c_{B7} = \frac{704.069}{521.869} 1.556 - \frac{704.069 - 521.869}{521.869}(0.92)(2.046)$$
$$= 1.443 \text{ dollars}/10^6 \text{ Btu}$$

In order to apply equation (2b) to the evaluation of c_{B6}, the appropriate throttle steam is that from the reheater, at unit cost c_{RH}. The annual cost of reheat steam $c_{RH}A_{RH}$ equals that of the steam supplied to the reheater $c_{B7}m_{RH}a_{B7}$ plus the fuel expense for the reheater $c_F A_{F,RH}$,

$$c_{RH} m_{RH} a_{RH} = c_{B7} m_{RH} a_{B7} + c_F A_{F,RH}$$
$$= c_{B7} m_{RH} a_{B7} + c_F[m_{RH}(a_{RH} - a_{B7})/\eta_{\text{II},RH}]$$

where the definition of the second law efficiency of the reheater has been utilized. Then,

$$c_{RH} = \frac{a_{B7}}{a_{RH}} c_{B7} + \frac{a_{RH} - a_{B7}}{a_{RH}} \frac{c_F}{\eta_{\text{II},RH}} = \frac{a_{B7}}{a_{RH}}\left(c_{B7} - \frac{c_F}{\eta_{\text{II},RH}}\right) + \frac{c_F}{\eta_{\text{II},RH}}$$

The value of a_{B7} has already been calculated, 521.869 Btu/lb, and a_{RH} can be readily evaluated in the same way; hence,[7,8]

$$c_{RH} = \frac{521.869}{631.999}\left(1.443 - \frac{0.80}{0.514}\right) + \frac{0.80}{0.514} = 1.531 \text{ dollars}/10^6 \text{ Btu}$$

Thus, with $a_{B6} = 529.630$ Btu/lb calculated from the data of Table 2, equation (2b) gives:

$$c_{B6} = \frac{631.999}{529.630} 1.531 - \frac{631.999 - 529.630}{529.630}(0.93)(2.046)$$

$$= 1.459 \text{ dollars}/10^6 \text{ Btu}$$

To get c_{B5} with equation (2b), the appropriate "throttle steam" is that at the conditions $B6$, and for c_{B4} it is that at the conditions $B5$. Therefore, with $a_{B5} = 429.123$ Btu/lb and $a_{B4} = 366.153$ Btu/lb

$$c_{B5} = \frac{529.650}{429.123} 1.459 - \frac{529.630 - 429.123}{429.123}(0.93)(2.046)$$
$$= 1.354 \text{ dollars}/10^6 \text{ Btu}$$

[6] $[h - h_0]$ and $[s - s_0]$ are the enthalpy and entropy of the reactants relative to the products when one pound of fuel is brought to complete, stable equilibrium with the ambient environment.

[7] It is assumed that the second law efficiency of the high pressure and reheat sections of the boiler are the same, equal to that of the overall boiler, inasmuch as the temperatures of the H_2O at the inlet of the two sections are virtually the same, as well as those at the outlets.

[8] Notice that the value for c_{RH} is very close to $(0.8/0.514) = 1.556$; in other words, the first term of the expression for c_{RH} is small. It should be mentioned that, theoretically, the formula for c_T should have another term, besides (0.8/0.514), inasmuch as the feedwater flowing into the high pressure boiler already has some availability. But the unit cost of the feedwater c_1 could be obtained from the *results* of the present analysis (see footnote 9, subsequently); the exact value of c_T could then be obtained by iteration. However, the consequent correction to $c_F/\eta_{\text{II,boiler}}$ is small, and is probably smaller than the error in c_T from other inaccuracies.

Table 4 Cash flow analysis, feedwater heater replacement evaluation

Year	0	1976	1977	....	1995
Fuel and Maintenance Saving		$ 27,355	$ 28,996		$82,764
- Depreciation (S.Y.D.) of Replacement Heater		20,000	19,111		3,111
- Ad Valorem Taxes		5,640	5,499		2,961
= Taxable Balance		$ 1,715	$ 4,386		$76,692
- Income Taxes		858	2,193		38,346
+ Investment Tax Credit	$ 23,500				
= After Tax Balance	$ 23,500	$ 858	$ 2,193		$38,346
+ Depreciation		20,000	19,111		3,111
+ Salvage Value of Replacement Heater					18,000
- Heater Replacement Cost	235,000				
= Total Cash Flow	-$211,500	$ 20,858	$ 21,304		$59,457
x Present Worth Factor (@ 9%)	1.0	.9174	.8417		.1784
= Discounted Cash Flow	-$211,500	$ 19,134	$ 17,932		$10,607
Cumulative Total of Discounted Cash Flow	-$211,500	-$192,366	-$174,434		+$29,166

$$c_{B4} = \frac{429.123}{366.153} 1.354 - \frac{429.123 - 366.153}{366.153} (0.90)(2.046)$$
$$= 1.270 \text{ dollars}/10^6 \text{ Btu}$$

The foregoing unit costs, along with the useful energy requirements calculated in the previous section, allow the hourly fuel costs for feedwater heating to be evaluated.

Fuel Costs for Feedwater Heating

The hourly cost of feedwater heating for each of the three cases at hand can now be calculated. For example, for Case C,

$$\text{dollars/hr} = c_{B4}A_{B4} + c_{B5}A_{B5} + c_{B6}A_{B6} + c_{B7}A_{B7} + c_F A_{F,\text{additional}}$$
$$= 1.270(39.069) + 1.354(0) + 1.459(72.08) + 1.443(99.05) + 0.8(26.945) = 319.267 \text{ dollars/hr}$$

Each of these hourly costs has been tabulated in Table 3, for all three cases.[9]

Economic Justifiability of Heater Replacement

On the basis of the hourly costs of feedwater heating shown in Table 3, the annual cost associated with the deteriorated heater can be estimated. In turn, via economic analysis, this cost can be put on an equivalent basis with the investment required for replacing or retubing the heater, to see if the investment is justified. Any number of methods for economic analysis could be employed; here, a discounted cash flow analysis will be used, to illustrate the application of the results embodied in Table 3.

If the unit operates 8000 hr per yr at a 70-percent capacity factor, the calculated additional annual fuel cost due to the deterioration of the heater No. 5 is:[10]

$$8000 \frac{\text{hr}}{\text{yr}} (0.70)(295.957 - 294.093) \frac{\text{dollars}}{\text{hr}} = 10{,}438 \frac{\text{dollars}}{\text{yr}}$$

And if the heater is out of service for 3 weeks per year for the plugging of heater tubes, the annual heater downtime fuel cost is:

$$3 \frac{\text{weeks}}{\text{yr}} \left(168 \frac{\text{hr}}{\text{week}}\right) (319.267 - 294.093) \frac{\text{dollars}}{\text{hr}} = 12{,}688 \frac{\text{dollars}}{\text{yr}}$$

In addition to the additional fuel costs accrued during heater outage, a manpower expenditure is required to plug the leaks. If 15 leaks per year occur and if 28 man-hr are charged at 10.07 dollars/man-hour during each heater outage the annual additional maintenance expenditure is:

$$15 \frac{\text{outages}}{\text{year}} \left(28 \frac{\text{man-hr}}{\text{outage}}\right)\left(\frac{10.07 \text{ dollars}}{\text{man-hr}}\right) = 4229 \frac{\text{dollars}}{\text{yr}}$$

Then the total annual additional fuel and maintenance expenditure due to heater number 5 is:

$$10{,}438 + 12{,}688 + 4{,}229 = 27{,}355 (\text{dollars/yr})$$

Assume that: (*a*) the heater replacement cost is 235,000 dollars, (*b*) the replacement heater will have a 20 year life and an 18,000 dollar salvage value, (*c*) fuel and maintenance savings are escalated at 6 percent per year, (*d*) after tax cost of capital is 9 percent. Table 4 shows the results of a cash flow analysis of the proposed investment in a replacement heater. As is indicated, since the net cumulative discounted cash flow (+29,166 dollars) is positive, the replacement of the heater is justified. The heater should be replaced.

Alternatively the heater might be retubed, rather than replaced. However it then may have to be removed from service for an extended period of time. If the heater could be retubed for 185,000 dollars (versus 235,000 dollars for replacement), a savings can be realized if retubing can be accomplished in less than:

$$\frac{(235{,}000\text{–}185{,}000 \text{ dollars})}{(319.267\text{–}294.093 \text{ dollars})/\text{hr}} = 1986 \text{ hr} = 11.8 \text{ weeks}$$

where the denominator is the additional fuel expenditure due to heater downtime.

In equation (1) there are two components to the cost of product useful energy; one contribution from fuel expense and one from capital investment. The useful energy costs employed in the present analysis, (c_B, c_T, c_s and c_{RH}) do not include capital expenses. Capital costs are

[9] The unit cost c_1 of boiler feedwater could be obtained from these hourly costs by dividing the total hourly cost of feedwater heating, including heaters 1–3 as well, by $A_1 = m_1[h - h_0 - T_0(s - s_0)] = m_1 c_p[T_1 - T_0 - \ln(T_1/T_0)] =$ 213,010,000 Btu/hr. Also, c_1 can be estimated by dividing the average unit cost of "fuel" for feedwater heating, say 1.40 dollars, by the average 2nd-law efficiency of feedwater heating [8], 0.9:$c_1 \approx 1.40/0.9 = 1.555$ dollars/10^6 Btu.

[10] The use of a simple capacity factor is tantamount to assuming that the hourly costs vary in proportion to the load on the unit. This is a good assumption since the second law efficiencies, underlying the unit costs, do not vary much with load [8].

not neglected; they are irrelevant. Because, the capital for all the equipment involved in supplying useful energy to the feedwater heaters is already sunk. However, it should be noted that other differential costs may be applicable to the deterioration of heater performance. For example, if the cycle efficiency decreases greatly, and if the boiler does not have sufficient overcapacity, the loss of unit efficiency will cause a decrease in maximum output, and hence could require the expenditure of additional capital. This would result in an added monetary benefit possible through replacement of the feedwater heaters in question.

Closure

It has been demonstrated that the operating cost differentials due to the loss of efficiency of feedwater heaters can be readily obtained by calculating the useful energy requirements of the feedwater heaters under design as well as deteriorated conditions, and by properly evaluating the value of this useful energy. Application of these techniques leads to a straightforward method for determining when a heater should be replaced.

The method is more reliable than alternates (*a*), (*c*), and (*d*) mentioned in the Introduction. And it is more direct than method (*b*), inasmuch as it is not necessary to ascertain the effects of deteriorated heater performance on the thermodynamic properties and flow rates at every juncture of the cycle. While application of the 2nd-law method does require evaluation of the 2nd-law efficiency of the devices (efficiencies taken from [8] for this paper) those calculations need be performed only once during the unit's lifetime. As a shortcut, reasonable accuracy can be obtained by substituting efficiencies from [8], for similar cycles. It should also be mentioned that the unit costs at the various junctures need to be calculated only once in a lifetime; then they are readily available for analyses like the present one, for any device in the cycle as well as for feedwater heaters.

The solution of this actual power plant problem by useful energy analysis has been used to demonstrate the techniques and the utility of this application of the second law of thermodynamics. The concepts presented provide a fundamental tool for the practicing engineer.

Analyses of this type have already led to significant savings in construction and operating costs at Wisconsin Electric [13]. This is substantiated by a second analysis, involving the determination of the operating costs associated with driving boiler feed pumps with a steam turbine compared with driving the pump with an electric motor, which will be presented in another article.

While the analysis presented here was for a plant operating problem, the same methods could be applied at the design stage, for ascertaining the desirability of prospective improvements—for design optimization. Then, capital costs must also be taken into account, in the manner of equation (1).

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