Data Sheet 12

Results of Optimization of Heater Design Conditions

S = $6, 14/sq ft; B = $8000/Btu/kwhr; I = $100/kw

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FOR HTR COST, BTU VALUE, AND KW CREDIT=$ 6     $ 8000     $ 100
THE LEVERAGE FACTOR F, IS 2.132
AND OPTIMUM DESIGN CONDITIONS ARE AS FOLLOWS:

HTR     OPT.      OPT.                COND     DR CLR
NO.     TD        DCTD      DIFF.     RISE      RISE
 6      2.75      6.33      3.58      52     9.5
 5      3.88      9.64      5.76      34.3      7.5
 4      7.4     NO DRAIN COOLER       36.2      0
 3      4.83      3.15     -1.68      69.4      5.8
 2      2.17      3.69      1.52      51     7.5
 1      2.53      9.47      6.94      42.6      8.8
     AVERAGE OPTIMUM T.D. ON 6 HEATERS = 3.9
     AVERAGE OPTIMUM DC T.D. ON 5 HEATERS = 6.5
***

FOR HTR COST, BTU VALUE, AND KW CREDIT=$ 14    $ 8000     $ 100
THE LEVERAGE FACTOR F, IS 2.132
AND OPTIMUM DESIGN CONDITIONS ARE AS FOLLOWS:

HTR     OPT.      OPT.                COND     DR CLR
NO.     TD        DCTD      DIFF.     RISE      RISE
 6      6.07      13     6.93      52.5      9
 5      8.17      17.74     9.57      35.1      6.7
 4      14.7    NO DRAIN COOLER       36.2      0
 3      10.48     7.01     -3.47      69.3      5.9
 2      4.82      7.94      3.12      51.2      7.3
 1      5.55      17.83     12.28     43.6      7.8
     AVERAGE OPTIMUM T.D. ON 6 HEATERS = 8.3
     AVERAGE OPTIMUM DC T.D. ON 5 HEATERS = 12.7
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Data Sheet 13

Results of Optimization of Heater Design Conditions

S = $10/sq ft; B = $8000/Btu/kwhr; I = $0, 50/kw

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FOR HTR COST, BTU VALUE, AND KW CREDIT=$ 10    $ 8000     $ 0
THE LEVERAGE FACTOR F, IS 1
AND OPTIMUM DESIGN CONDITIONS ARE AS FOLLOWS:

HTR     OPT.      OPT.                COND     DR CLR
NO.     TD        DCTD      DIFF.     RISE      RISE
 6      8.83      18.01     9.18      52.9      8.6
 5      11.57     23.23     11.66     35.5      6.3
 4      20.2    NO DRAIN COOLER       36.2      0
 3      15.08     10.27    -4.81      69.2      6
 2      7.06      11.35     4.28      51.3      7.2
 1      8.06      23.48     15.43     44.2      7.2
     AVERAGE OPTIMUM T.D. ON 6 HEATERS = 11.8
     AVERAGE OPTIMUM DC T.D. ON 5 HEATERS = 17.3
***

FOR HTR COST, BTU VALUE, AND KW CREDIT=$ 10    $ 8000     $ 50
THE LEVERAGE FACTOR F, IS 1.566
AND OPTIMUM DESIGN CONDITIONS ARE AS FOLLOWS:

HTR     OPT.      OPT.                COND     DR CLR
NO.     TD        DCTD      DIFF.     RISE      RISE
 6      5.91      12.71     6.79      52.5      9
 5      7.98      17.42     9.44      35     6.8
 4      14.4    NO DRAIN COOLER       36.2      0
 3      10.22     6.83     -3.39      69.3      5.9
 2      4.7       7.75      3.05      51.2      7.3
 1      5.41      17.49     12.08     43.6      7.8
     AVERAGE OPTIMUM T.D. ON 6 HEATERS = 8.1
     AVERAGE OPTIMUM DC T.D. ON 5 HEATERS = 12.4
***
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DISCUSSION

P. Leung and R. E. Moore[5]

The author has presented an excellent analysis of closed feedwater heater design optimization for nuclear power cycles. His efforts have obviously been extensive, and we wish to commend the clarity and completeness of the presentation. The results indicate the necessity for, and the justification of, detailed cycle analyses in determining the feedwater heater cycle arrangement, total heat transfer surface, and individual heater surfaces. Availability of computer programs and high computational speed have made these systems engineering approaches and cost effectiveness studies feasible. The overall cost savings to be realized by optimization are determinable and often highly significant.

The author's approach in varying the economic evaluation parameters of heater surface cost, capitalized value of change in heat rate, and credit for incremental power is of particular value to the power plant designer and adds to the significance of this paper. These evaluation parameters will be different for almost every plant as individual owner's fixed charge rates, fuel costs, capacity factors, incremental installation costs vary, and as heater pricing varies.

It is noted that the method of approach is based upon a constant thermal output of the nuclear steam generator. Thus, it is valid to claim a direct increase in kilowatt output resulting from heat rate improvement through feedwater heater optimization in a nuclear reactor plant cycle. The "double leverage" concept, is therefore, meaningful. For a fossil-fueled boiler plant cycle, however, the constant thermal output approach is thought to be less feasible. The fossil-fueled boiler is not normally rated by total thermal output. Water flow rates and heating surface distribution among economizer and water wall sections, steam flow rates and heating surface distribution among superheaters, and reheater sections, type of fuel burned, and exit gas temperatures all play major roles in the design and pricing of the boiler, and make constant thermal output assumptions impractical.

In optimizing closed feedwater heaters in the fossil-fueled boiler plant cycle, the resulting variations in final feedwater temperature, reheater flows, and main steam flow from the superheater all affect the design characteristics, and, consequently, the total heat absorption rates and overall boiler costs. In addition, overall plant heat rates and kilowatt output change with feedwater heater optimization. For example, assuming *constant throttle steam flow* at specified throttle steam conditions, a rise in final feedwater temperature above that of a base cycle will produce a gain in heat rate. The gain will be accompanied by a reduction in boiler total thermal output and a reduction in kilowatt output. In order to maintain a *constant boiler total thermal output*, increases in both feedwater and main steam flow would be necessary. As the heat rate has been improved, a slight gain in kilowatt output above the base case can be expected. If *kilowatt output is held constant* between cases, the boiler total thermal output would be slightly reduced, and the steam flow would be slightly increased. The economics between a reduction in boiler cost due to lower total thermal output, and an increase in boiler cost due to increased flow and higher kilowatt output must be carefully evaluated to attain the optimum plant cycle.

Because of the complexity of analyzing these fossil-fueled cycles when three major parameters, i.e., kilowatt output of the turbine, boiler total thermal output, and main steam flow, vary with each change in heater design parameters, we have found it more feasible and accurate to hold the kilowatt output constant. We presented an ASME paper entitled "Thermodynamic and Economic Analyses of Closed Feedwater Heaters for Supercritical Pressure Steam Turbine Cycles" (67 — WA/Pwr-5) at the 1967 ASME Winter Annual Meeting. The *constant kilowatt* method of approach was employed as feedwater heater design parameters were varied.

In our presentation, an 806 Mw supercritical pressure turbine cycle with seven stages of regenerative heating was selected as a base cycle. Final feedwater temperature was at 498.2 F with the highest pressure heater receiving steam from the cold reheat point. When the top heater terminal temperature difference was changed from 0 F to −5 F, the final feedwater temperature increased to 502. 9 F.

For a *constant kilowatt* output approach, this change in final feedwater temperature would affect the boiler as follows:

Throttle steam flow:	+24,000 lb/hr (+0.45 percent)
Reheat steam flow:	(−) 12,000 lb/hr (−0.25 percent)
Boiler total thermal output:	(−) 0.12 percent
Kilowatt output:	constant

When the *constant thermal* output approach is employed, the following changes, compared to the base case, would occur:

Throttle steam flow:	+28,400 lb/hr (+0.54 percent)

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[5] Bechtel Corp., Vernon Division. Mems. ASME

Reheat steam flow:	(−) 13,200 lb/hr (−0.275 percent)
Boiler total thermal output:	0 percent
Kilowatt output:	+790 kw

After careful comparison of these two approaches, we selected the constant kilowatt approach for these reasons:

1 The base cycle selected was from a turbine valve—wide-open point heat balance. The kilowatt output was at maximum expected (not guaranteed). If an additional 790 kilowatt output is to be realized, additional wheel generation from the turbine and additional Kva from the generator must be specified and paid for.

2 Incremental kilowatt credit, the fair value of which is often difficult to establish, is eliminated as an evaluation factor.

It is interesting to note the parallel conclusions reached in Mr. Salisbury's paper for nuclear cycles and in our presentation for fossil-fueled cycles. These conclusions are summarized below:

1 The change in heat rate is linear with respect to change in heater terminal temperature differences and approach temperature differences.

2 As feedwater heater parameters are changed as a group, the overall change in heat rate is the same as the summation of the change in heat rate attributable to individual heaters.

3 The heat rate effect of each degree of variation in heater terminal temperature difference is much more significant than the heat rate effect of each degree of variation in drain cooler approach temperature difference.

4 Changes in parameters of the highest pressure heater exert the most significant influence on the heat rate.

5 Economic gains realizable through computer optimization studies are significant, and, therefore, efforts to determine the best balance between equipment capital costs and operating costs are justifiable.

It is noted that the author has utilized a "capitalized" rather than a "present worth" cost method in the economic analyses. Based on similar studies performed by the discussers using the "present worth" approach, it is believed that the results would not be significantly different from those presented in this paper.

R. W. Pinder[6]

Considerable effort has been applied in the last few years to improve the efficiency of the nuclear plant power cycle. The reward for these efforts has been an improvement in heat rate of more than 400 Btu/kwh. This has been a combined effort of the nuclear system and turbine manufacturers, architect-engineers, and consultants, such as the author of this paper. The improvements the author has presented in this paper are another important step in the evolution of the nuclear power cycle.

The method presented in the paper for the optimization of the condensing section and drain cooler terminal differences is a very useful tool in establishing the optimum plant cycle. It is even more applicable at the present time because of the increased emphasis on reducing plant costs. This writer feels that there is more emphasis applied to the cycle today because of the establishment firm reactor/turbine interface conditions and established turbine designs. In the past, more emphasis was placed on the interface conditions and nuclear system than on the regenerative cycle during cycle optimization.

The examples and illustrations in the paper that show the gain available as a function of the evaluation parameters are a definite aid in giving the designer an idea of the effect of these changes. The illustrations of the dependency of optimum conditions on the evaluation parameters used in this paper emphasize the importance of establishing the most accurate evaluation parameters possible.

E. H. Miller[7]

Mr. Salisbury has developed and presented a practical technique for solving the difficult optimization process leading to the specification of feed-water heater and drain cooler terminal temperature difference. He shows that there are significant economic gains to be achieved by rigorously carrying out this optimization step as compared to the relatively common practice of using a single value for terminal difference applied to all or most of the heaters.

Regretfully, the optimization technique did not yield to the easily visualized parameters and hand calculation procedures which the author used so successfully in developing and understanding the regenerative cycle[8,9] The present widespread availability of digital computers should make this a negligible objection to most power plant designers.

Author's Closure

The author is most grateful to Messrs. Leung and Moore for their kind words, and pleased to observe the several areas in which his work agrees with theirs. They have re-emphasized the economic importance of matching the heater system to the available extraction openings in power plant cycles. Although the author has worked intensively with such systems over many years, never has it been possible in the past to achieve such fineness of resolution of the optimization problem until the advent of modern high-speed computers. What then would

Data Sheet 14

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ASSIGN EVALUATIØN PARAMETERS: S,S6,B,I,U9? 5,7,15000,100,1

                       ****ØPTIMUM CYCLE****
                       (BASED ØN 371 HB 975)

FØR HEATER CØSTS,S AND S6, ØF $ 5  7.   PER SQ FT
FØR HT TRANSFER CØEFF ØF 450  AND 650
FØR CAPITALIZED VALUE, B, ØF HEAT RATE ØF $ 15000   PER BTU/KWHR
FØR INCREMENTAL KW CREDIT, I, ØF $ 100  PER KW
WHICH GIVES A LEVERAGE FACTØR,F, ØF 1.79416
THE ØPTIMUM DESIGN CØNDITIØNS HTR BY HTR ARE AS FØLLØWS:

HTR       ØPT.      ØPT.                 CØND   DR CLR
NØ.       TD        DCTD      DIFF       RISE    RISE
 6        2.83      5.98      3.15       55.1   9.3
 5        2.74      6.48      3.74       37.9   8.7
 4        4.42      5.58      1.15       22.3   10.3
 3        4.57     NØ DRAIN CØØLER       68.8   0
 2        1.56      2.29      .73        56.6   3.8
 1        1.55      6.84      5.29       41.9   5.4

   FW H     HT RATE  CØND FLØW  MWE      UEEP     TH MW    TH FLØW
   399.6    9689.59  7.51393  1159.82  1001.17  3292.9   14.1752

FØR FW H= 399.595
HTR                D.C.
N3.      T.D.      T.D.       STM SURF     DC SURF     TH FLØW
 6       2.83      5.98        65785.3     12811.1     14.1752
 5       2.74      6.48        59376.6     14871.9     14.1752
 4       4.42      5.58        39171.9     24013.1     14.1752
 3       4.57      NØNE        37464.0          .0     14.1752
 2       1.56      2.29        49605.1      4279.7     14.1752
 1       1.55      6.84        46507.6      5849.1     14.1752
CØND SURF= 297910. D.C. SURF= 61824.9 TØTAL= 359735.

                    ****REFERENCE CYCLE****

FØR FW H= 397.6
HTR                D.C.
NØ.      T.D.      T.D.       STM SURF     DC SURF     TH FLØW
 6       5.00     10.00        54324.0     10233.8     14.1397
 5       5.00     10.00        46714.6     11496.1     14.1397
 4       5.00     10.00        37717.3     15873.1     14.1397
 3       5.00      NØNE        36770.0          .0     14.1397
 2       5.00     10.00        34404.6      2415.6     14.1397
 1       5.00     10.00        30520.3      4589.9     14.1397
CØND SURF= 240451. D.C. SURF= 44608.5 TØTAL= 285059.

                        +++++RESULTS+++++
                  CHANGE IN HEAT RATE          =-23.098  BTU/KWHR
                  CHANGE IN ØUTPUT             = 2751.28 KILØWATTS,
                  CHANGE IN L.P. SURFACE       = 60637.5 SQ FT
                  CHANGE IN H.P. SURFACE       = 14038.5 SQ FT
                  T3TAL CHANGE IN SURFACE      = 74676.1 SQ FT
                  DØLLAR CHANGE IN EVALUATIØN  =-220140.
                                           J.K. SALISBURY
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[6] Atomic Power Equipment Department, General Electric Company, San Jose, Calif.

[7] Manager, Thermal Development Engineering, General Electric Co., Schenectady, N. Y.

[8] Salisbury, J. K., "Steam Turbine Regenerative Cycle—An Analytical Approach," Trans. ASME, April 1942, Vol. 64, pp. 231–245.

[9] Salisbury, J. K., *Steam Turbines and Their Cycles*, Wiley, N. Y., 1950.

have taken weeks or months (at high cost in both eyesight and manpower), now can be done with superb accuracy in seconds, at a cost of only a few dollars in computer time, once the program has been perfected.

Another major problem in power plants that yields readily to the method presented in the paper is the optimization of the design of multipressure condensers. The author has recently computerized such an approach for the discussers' company, with complete success.

The age-old question of whether an evaluation shall be made at constant *output* (kilowatts) or at constant *input* (thermal megawatts) has many facets. In the first alternative, one evades the issue of seeking the elusive and volatile value of an incremental kilowatt, but substitutes for such effort the evaluation of changes in cost of the boiler, reheater, fuel system, etc. In the second alternative, when the input is a fixed quantity, the incremental kilowatt value *must* be arrived at, even though it will vary from system to system and from utility to utility. It seems to the author that if one is meticulous in considering *all* costs on a true basis, the results should vary very little indeed.

In one particular instance, the nuclear plant, we believe that the constant *input* method, as used in the paper, is preferable. Since reactors are sold at fixed thermal ratings, and generally are unavailable in small size gradations, whereas turbine-generators may vary continuously in rating, with well-known accompanying price changes, it seems logical to adopt what seems to the writer to be the "one-dimensional" approach: constant input and variable output.

For fossil-fired plants, where small gradations in steam flow or reheater duty are readily achieved, we must agree that the choice is by no means as clear, provided incremental changes in cost, as a function of the various possible cycle changes, are readily available. With the constant output, variable input approach it is necessary to evaluate the cost of each of the several changes that take place, that is throttle flow, reheater flow, reheater duty, etc. If the output (kilowatts) are the dependent variable, only one cost change must be considered, although admittedly it may be more difficult to pin down.

Mr. Pinder's comments are acknowledged. They are based on an association with the author over a period of several years, and a continuing intense interest in the development of better nuclear power cycles.

Mr. Miller has also recognized and emphasized the economic gains that result from cycle optimization. We agree that hand calculation methods might make the method available to more users, and the effects more readily visualized. However, since presentation of the paper the author has developed an accurate and flexible computer program that not only optimizes the heater design conditions, but also produces the net changes in heat rate, output, total heater surface, all heat balance data, and net evaluated plant cost in dollars, for any set of heater costs, heat rate valuation, incremental kilowatt credit, and heat transfer coefficients. The savings in time alone, over hand calculations, not to speak of the greater accuracy and ease of evaluating alternatives, is ample justification for the use of computer methods.

Data sheet 14 is a sample of the results that are produced by the program for an 1150 Mwe plant. Heat balance data are omitted for space reasons. Note that all heater design conditions for the optimum cycle are appreciably lower than the 5 deg/10 deg of the reference cycle, that heat rate and output are improved, and that there is a $220,000 reduction in evaluated cost.