Ratio Analysis - Combined Cycle Studies

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Ratio Analysis

abstract

There is a simple tool available that can be used to analyze changes in unit performance. The unique property of this tool is that it requires very basic data that is generally recorded daily for all operating units. Another property is that it is possible to compare between different units, at different loads and between different modes of operation (base load vs. regulation) with good repeatable results. The procedure can identify the cause of unit performance changes to a resolution of turbine or boiler cycles and/or fuel accounting error. When used in conjunction with a benchmark heat rate curve, can identify changes in heat rate to a resolution of major component groups within a cycle.

The data required to do this is: Generation (gkwh)
Station Usage (kwh)
Steam Generated (lbm)
Coal Burned (tons)
Coal heating value (btu/lbm)

This paper is dedicated to generation performance engineers. In particular, those who have had to account for thermal performance between different units, at different loads, between different years or months and with little or no credible data, or little hope of finding any.

bill brockman

Introduction

A long time has passed since the State of Kentucky decided to audit the investor owned electric utility companies within its borders. During the audit there were many questions asked about the current heat rate of units, and why they differed from design, or why they differed at all from month to month. When I am asked by a non technical person "What is the heat rate of Kentucky Utilities Company ?" , I tell them "that is like asking -- What is the temperature in North America ?". Its a simple question that by necessity, requires a dynamic answer.

It is said that necessity is the mother of invention, and so it is in this case. One day while pondering the temperature in North America, I wondered about how to account for changes in heat rate from a time before I worked with the company. The answers required there to be little test data. It struck me that the simple heat rate calculation -- using coal burn, generation etc. etc. may hold some answer, and indeed it did. In fact, I invented a basic relation which involved data that was obtainable in monthly operating reports that answered most of the questions asked.

Under all circumstances:

Heat rate = the heat it takes to make a pound of steam (x) the pounds of steam it takes to make a gross kilowatt (x) the gross kilowatts per net kilowatt (a multiplier)

BASIC RELATIONS & THEORY

The basic relations of this tool no doubt seem too elementary to do much good, until you look at them more closely.

Heat Rate = btu input/ lb steam (x) lb steam/ gross kw (x) gross kw/ net kw

btu input/ lb steam	lb steam/ gross kw	gross kw/ net kw
|	|	|
BOILER EFF.	**TURBINE EFF.**	**STATION USE**

It is conceivable, that over a period of time, the average steam temperatures and pressures would be representative of normal operation for a unit. Thus one could say that the btu's input to a boiler it takes to make a pound of steam could represent the relative boiler efficiency, or perhaps index it. The second term is referred to as water rate, and is often used to monitor the performance of the turbine cycle. The last term is the reciprocal of the common % station usage and is a multiplier for gross heat rate.

We now have a relation that defines heat rate as a product of boiler performance , turbine performance and station usage indexed to simple ratios. Conveniently, these ratios can be generated from historic data and can also be quantified over time. However, it doesn't do much for the person trying to account for changes in heat rate over a broad range of conditions or different units. One approach to address this problem was considered using differential calculus, specifically the relation of the total differential.

By using the calculations for the total derivative as a function of load, we can arrive at an expression that is functional for changes in heat rate.

if:

$$NUHR := \frac{BTU}{LBS} \cdot \frac{LBS}{GKW} \cdot \frac{GKW}{NKW}$$

and:

$$B := \frac{BTU}{LBS} \quad \text{(BOILER)}$$

$$T := \frac{LBS}{GKW} \quad \text{(TURBINE)}$$

$$S := \frac{GKW}{NKW} \quad \text{(STATION USE)}$$

$$L = \text{Load} \quad \text{(NKW)}$$

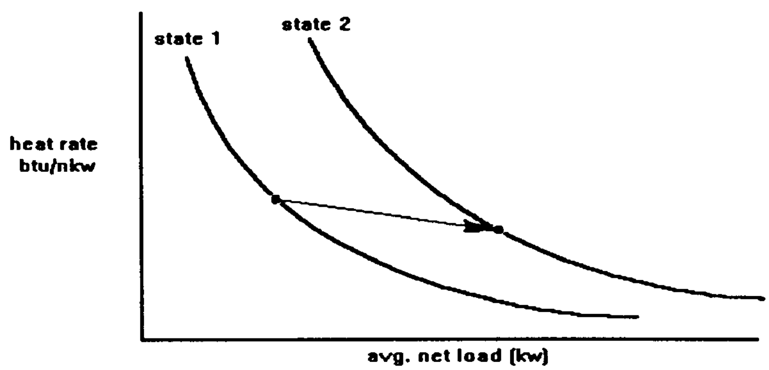
then:

$$NUHR := B \cdot T \cdot S$$

and the TOTAL DERIVITIVE is:

$$\frac{d}{dL} NUHR := \left[\left(\frac{d}{dB} NUHR \right) \cdot \frac{d}{dL} B \right] + \left[\left(\frac{d}{dT} NUHR \right) \cdot \frac{d}{dL} T \right] + \left[\left(\frac{d}{dS} NUHR \right) \cdot \frac{d}{dL} S \right]$$

The calculus makes several assumptions. First it assumes that we have continuous relations between heat rate and load, boiler performance, turbine performance and station usage. Secondly it assumes that these relations all fall on a continuous smooth curve for which we have mathematical expressions. In the context of what we are doing, we have none of the above. What is needed is a relation that sufficiently describes the deviations between different units, different loads and different operating states.



If we go to the very basics of calculus, there is a method by which we can estimate a solution. This can be done with deviation analysis. The rudiments of the limit theorems.

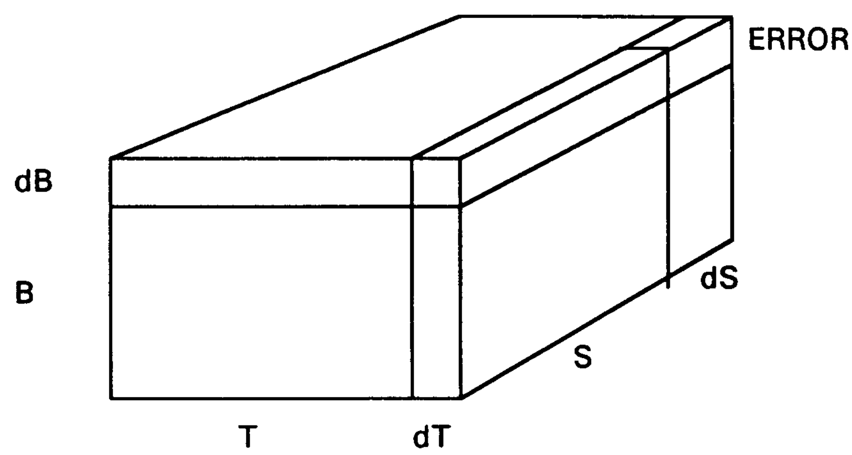
IF:

$$NUHR = B \cdot T \cdot S$$

THEN:

$$\Delta NUHR = (B + \Delta B) \cdot (T + \Delta T) \cdot (S + \Delta S) - B \cdot T \cdot S$$

This assumes no continuity, however there is inherent error. The larger the change in any one of the parameters, the larger the error will be. One way to look at this is by using a value block.



ERROR = dB x dT x (S + dS)

Thus it is possible, by identifying the change in the three ratios between any two operating states, to estimate the cause of change in heat rate. A problem occurs however, when we try to identify how much each ratio contributed to the total change.

$$\Delta NUHR = (B + \Delta B)\cdot(T + \Delta T)\cdot(S + \Delta S) - B\cdot T\cdot S$$

simplifies to

$$\Delta NUHR = B\cdot T\cdot \Delta S + B\cdot \Delta T\cdot S + B\cdot \Delta T\cdot \Delta S + \Delta B\cdot T\cdot S + \Delta B\cdot T\cdot \Delta S + \Delta B\cdot \Delta T\cdot S + \Delta B\cdot \Delta T\cdot \Delta S$$

When we simplify and try to break apart the expansion, we can't isolate any terms as the expression is presented. This makes it difficult to single out the contribution any one ratio has made to the total change in heat rate. However, there is a related expression that does just that, and gives very good results. The new expression is derived by eliminating the higher order terms of the simplified equation above. Then dividing by the net unit heat rate, we end up with a very functional equation.

given:

$$\Delta NUHR = (B\cdot T\cdot \Delta S) + (B\cdot \Delta T\cdot S) + \underset{\Lambda}{(B\cdot \Delta T\cdot \Delta S)} + (\Delta B\cdot T\cdot S) + \underset{\Lambda}{(\Delta B\cdot T\cdot \Delta S)} + \underset{\Lambda}{(\Delta B\cdot \Delta T\cdot S)} + \underset{\Lambda}{(\Delta B\cdot \Delta T\cdot \Delta S)}$$

and eliminate the higher order terms (assume smaller deviations):

gives:

$$\Delta NUHR = (B\cdot T\cdot \Delta S) + (B\cdot \Delta T\cdot S) + (\Delta B\cdot T\cdot S)$$

then deviding by NUHR gives:

$$\frac{\Delta NUHR}{NUHR} = \frac{B\cdot T\cdot \Delta S + (B\cdot \Delta T\cdot S) + (\Delta B\cdot T\cdot S)}{B\cdot T\cdot S} = \left(\frac{\Delta S}{S}\right) + \left(\frac{\Delta T}{T}\right) + \left(\frac{\Delta B}{B}\right)$$

The percent change in heat rate is approximately equal to the sum of the percent changes of the constituent variables.

$$\%NUHR \sim \%B + \%T + \%S$$

A comparison of both the deviation and percentage estimates are presented in Appendix (A). The attributes of the percent estimate is that the error is almost 1/2 the error of using the deviation estimate. The equation is in a form that lends itself easily to determining the contribution each ratio has made to the total change in heat rate. This equation, using the percent estimate, is the basis for using the ratios as a tool for studying changes in heat rate.

SAMPLE APPLICATION

1)BASIC RATIOS & Unit Change

This example identifies some basic changes to a units performance over a 6 month period. E. W. Brown Unit 2 showed an increase in heat rate from July to December even though the unit loading had increased, and there was a general decrease in backpressure.

DATA:	JULY 1992	DECEMBER 1992
GROSS MWH	62468	108345
NET MWH	57889	101017
MLBS STEAM	468140	771420
TONS COAL	24569	42958
BTU/LB COAL	12120.7	12342.5

JULY 1992	DECEMBER 1992
$HRJ := 10288.4$	$HRD := 10497.4$
$BJ := \frac{24569 \cdot 2 \cdot 12120.7}{468140}$	$BD := \frac{42958 \cdot 2 \cdot 12342.5}{771420}$
$TJ := \frac{468140}{62468}$	$TD := \frac{771420}{108345}$
$SJ := \frac{62468}{57889}$	$SD := \frac{108345}{101017}$

	$BJ = 1272.241$	$BD = 1374.631$	BOILER btu input/lb steam
RATIOS	$TJ = 7.494$	$TD = 7.12$	TURBINE lb steam/gkwh
	$SJ = 1.079$	$SD = 1.073$	STATION gkw/nkw

From the resulting ratios, we can see there has been an increase in the heat it takes to make a pound of steam (BOILER). Concurrently, the water rate has decreased indicating a relative improvement in turbine cycle performance (TURBINE), expected with lower backpressures. There has also been a slight reduction in the station use demand. The increase in heat rate is totally boiler related and / or attributed to fuel accounting.

ANALYSIS

$$\frac{HRD - HRJ}{HRD} = 0.0199 \qquad \left(\frac{BD - BJ}{BD}\right) = 0.0745 \qquad \left(\frac{TD - TJ}{TD}\right) = -0.0525 \qquad \left(\frac{SD - SJ}{SD}\right) = -0.0061$$

$$0.0199 \sim 0.745 - 0.0525 - 0.0061 = 0.0169$$

SAMPLE APPLICATION

2) BASIC RATIOS & Different Unit Comparisons

In January 1993, the operating reports for Ghent 3 and Ghent 4 showed that both units were loaded very nearly equal. However Ghent 3 heat rate was 600 btu/nkwh higher then Ghent 4. This was a significant change from the previous month. There were no performance tests conducted during the month to indicate the cause for such a change.

DATA - JANUARY 1993	GHENT 3	GHENT 4
GROSS MWH	250513	284814
NET MWH	231955	267535
STEAM GENERATED	1547100	1859200
TONS COAL BURNED	99082	107552
AVG. BTU/LB	12377.23	12401.32
REPORTED NUHR	10574.13	9970.93

===

RATIOS	$B3 = 1585.367$	$B4 = 1434.796$	BOILER btu input/lb steam
	$T3 = 6.176$	$T4 = 6.528$	TURBINE lb steam/gkwh
	$S3 = 1.08$	$S4 = 1.065$	STATION gkw/nkw

===

ESTIMATIONS

$$\frac{HR3 - HR4}{HR3} = 0.057$$ decimal heat rate increase

$$\left(\frac{B3 - B4}{B3}\right) = 0.095$$ decimal increase due to boiler cycle

$$\left(\frac{T3 - T4}{T3}\right) = -0.057$$ decimal decrease due to turbine cycle

$$\left(\frac{S3 - S4}{S3}\right) = 0.0143$$ decimal increase due to station use

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RATIO TOTALS 0.052

From this analysis, most of the high heat rate on Ghent 3 is due to relatively poor boiler performance. There is slightly more station usage on Ghent 3, but the turbine performance on Ghent 3 is better then on Ghent 4. The Boiler needs to be looked at.

MONITORING UNIT PERFORMANCE

A next logical step in using ratio analysis is to compare unit operating ratios against a performance benchmark. This is a departure from the original philosophy of this paper since it implies more real time data, and would take the place of comparing a window of operation against another window of operation. Instead, the comparison would be against a controlled ideal state. Since the operating state could be at any average load, the technical aspects of doing this become more complicated. A logical ideal state would be the units heat rate curve. Since most heat rate curves have been adjusted for standard operating conditions, it becomes necessary to gather additional data for any given window of operation. As a minimum, this additional data would be:

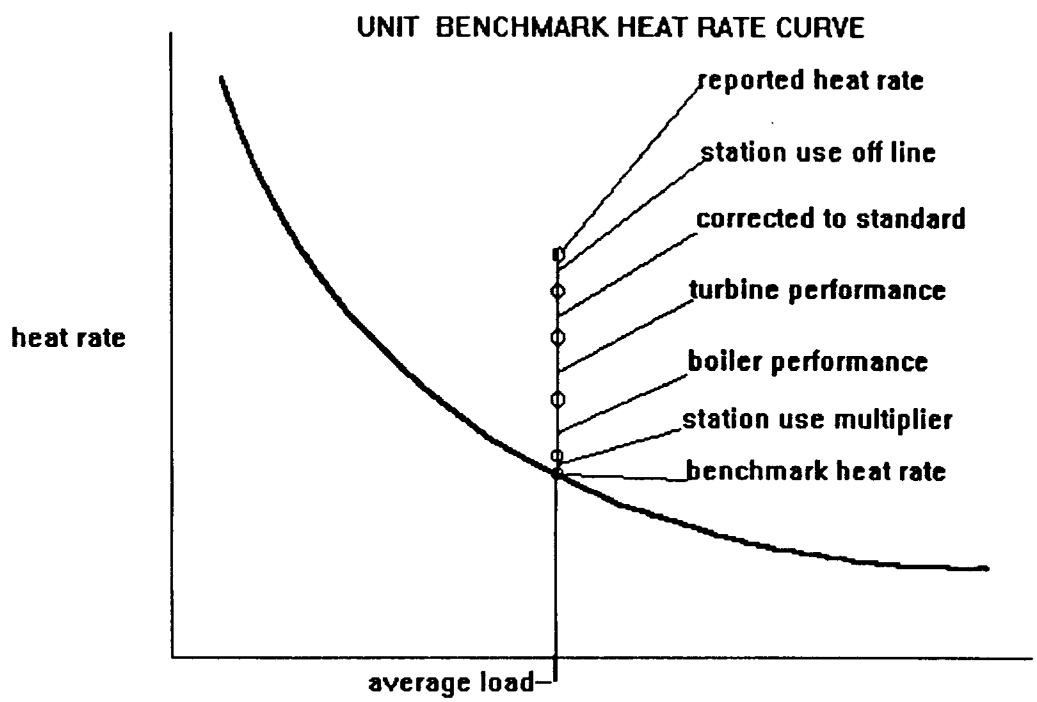
- time on line (hours & minutes)
- station use off line (mwh)
- average backpressure
- average throttle temperature
- average throttle pressure
- average reheat temperature (if applicable)

It is also necessary to generate three additional curve relations in addition to the heat rate curve. These curves represent the three ratios over the load range that correspond to the benchmark heat rate curve. These curves then would be:

- BTU/NKWH = f(net megawatts)
- BTU INPUT/ LB STEAM = f(net megawatts)
- LB STEAM/ GROSS MWH = f(net megawatts)
- GROSS MWH/ NET MWH = f(net megawatts)

The procedure would be to compile the data in the operating window of time. Adjust the heat rate for off line station usage, then correct the resulting heat rate to basic standard conditions with the OEM thermal kit. Using the average on line load, locate the benchmark ratios and heat rate. Then proceed with the remaining ratio analysis as described before. Obviously, this process is best done on a computer. The minimum time window should be daily operation. However, I have found that weekly operating data gives more credible results due to daily coal burn inconsistencies. This should not be the case where oil, gas or nuclear fuels are used.

The result of all this effort is a total macroscopic accounting of any change in unit performance. The total data necessary, other then the benchmark curves, still represents data that is gathered daily on each unit by operators. Most utilities now digitize this basic operating data for compiling monthly reports. The procedure outlined here could be easily implemented to not only indicate changes in performance, but also where that change occurred and by approximately how much.



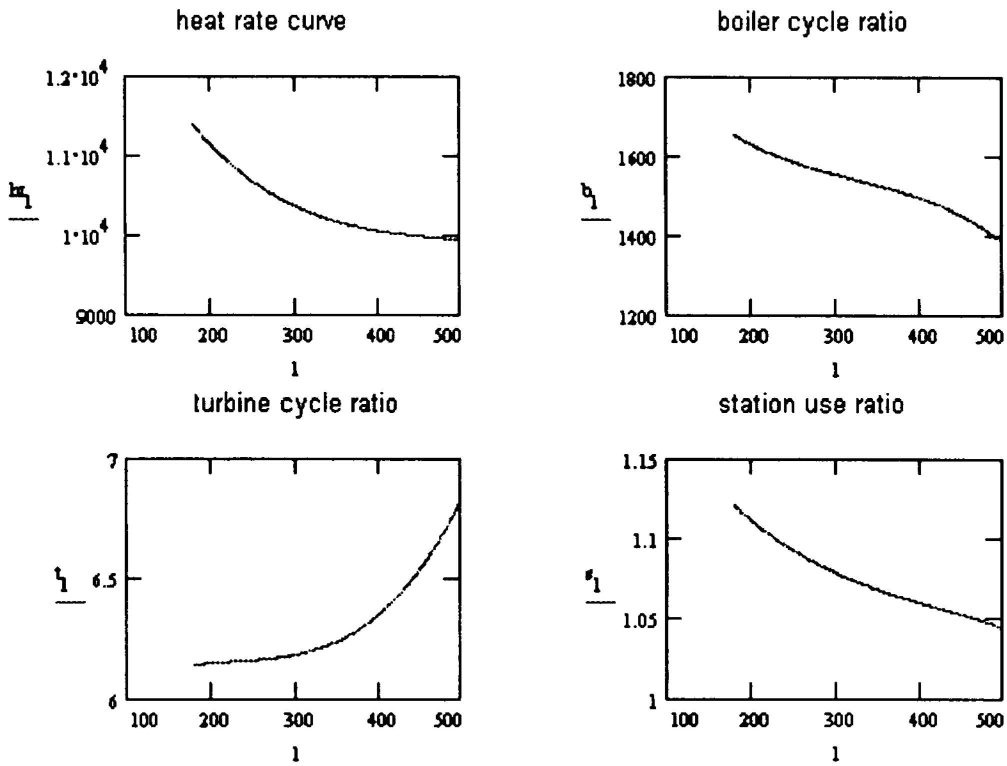
Although averages over the operating window are used, it has been found that using averages over a period of five or more operating days give meaningful results. If greater resolution is desired, then a rolling daily average over a week works very well.

An example of the family of ratio curves associated with a heat rate curve is:

MONITOR FILES -- GHENT UNIT 3 BENCHMARK 1992

net load range (mw) $\quad l := 180 .. 500$

heat rate -------	$hr_l := 15313.56 - (32.17668 \cdot l) + (.0666592 \cdot l^2) - (.0000476 \cdot l^3)$
boiler ratio -----	$b_l := 2127.87 - (4.308376 \cdot l) + (.0115047 \cdot l^2) - (.0000117 \cdot l^3)$
turbine ratio ---	$t_l := 5.753673 + (.0048274 \cdot l) - (.0000202 \cdot l^2) + (2.961168 \cdot 10^{-8} \cdot l^3)$
station use ----	$s_l := 1.263079 - (.0011457 \cdot l) + (.0000023 \cdot l^2) - (1.763701 \cdot 10^{-9} \cdot l^3)$



At any given average load: hr = b x t x s

These curves were produced using a third order least squares curve fit. Any source of data that is representative of a units operating performance over the load range is acceptable for this purpose. I have used both steady state turbine cycle tests as well as daily recorded data sorted by average load. Design data could also be used if the performance engineer felt comfortable using that as a benchmark. In any case, the benchmark curves should represent the best achievable performance at all loads.

EXAMPLE OF UNIT DATA CORRECTIONS

PERFORMANCE ACCOUNTING & CORRECTIONS
UNIT REPORT FOR GHENT 3
FROM 1 / 1 / 92 TO 1 / 31 / 92

ITEM	GENERATION (GMWH)	HEAT RATE (BTU/NKWH)	COST ($)
REPORTED DATA ------------	149185	10496.76	1903526
<u>CORRECTIONS</u>			
OFF LINE STATION ------------		-92.46972	-16768.85
STANDARD BACKPRESSURE	- 271.4219	-19.14453	-3471.751
RATED THROTTLE TEMP -----	11.625	5.028321	911.856
RATED THROTTLE PRES ------	-987.7031	6.97168	1264.274
RATED REHEAT TEMP ---------	0	0	0
T O T A L S -------------------------	148480.4	10397.14	1885462
BENCHMARK REF. DATA ---	148480.4	10291.08	1866229
UNACCOUNTED -----------		106.05	19232.76

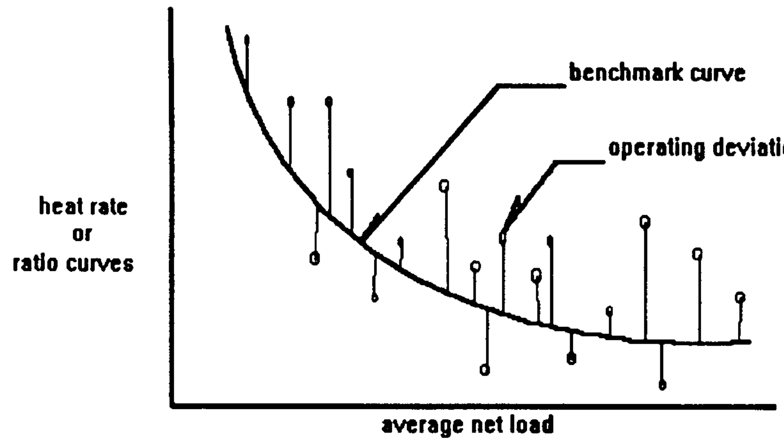
DIAGNOSTIC ANALYSIS - ENGINEERING REPORT
UNIT TO BENCHMARK COMPARISON
FOR GHENT 3
FROM 1 / 1 / 92 TO 1 / 31 / 92

REFERENCE HEAT RATE @ AVG NET LOAD ====	10291.08
TEST AVERAGE CORRECTED GROSS LOAD	342.51
TEST AVERAGE CORRECTED NET LOAD	318.10
REPORTED TEST HEAT RATE ===============	10496.76

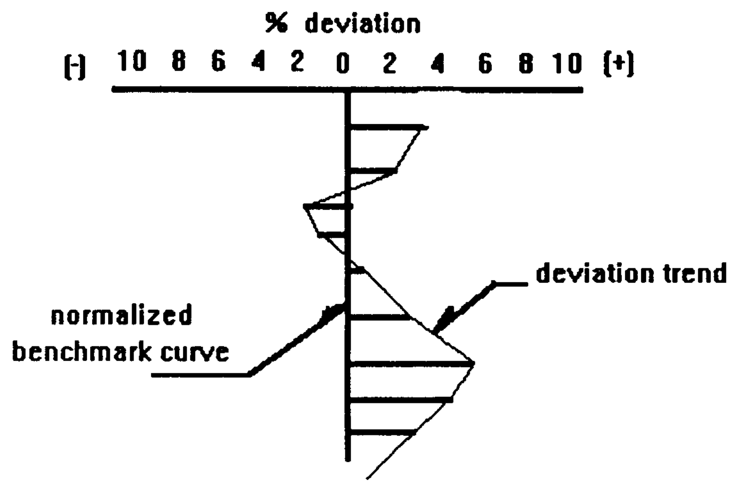
D I A G N O S T I C S	R E S U L T S	
OFF LINE STATION USE ==================	92.46972	10404.29
CORRECTED TO STANDARD CONDITIONS ===	7.14453	10397.14
BOILER AND/OR FUEL PERFORMANCE ======	-360.5619	10757.70
TURBINE CYCLE PERFORMANCE ==========	431.892	10325.00
STATION USAGE CHANGE ON PERFORMANCE =	20.7117	10305.10
TOTAL DIAGNOSTIC ACCOUNT ==========	191.65	10305.10

DATA TRENDS & PATTERNS

If operating data is gathered and processed on a regular interval, such as daily, then performance patters can be analyzed. This can best be accomplished by using the benchmark curves as the norm, then plotting all deviations relative to the norm.



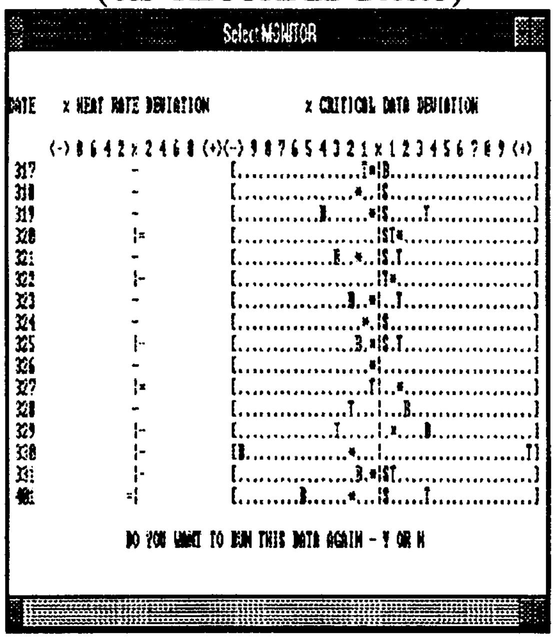
What this does is essentially linearize the benchmark curve and allows for a more visible pattern of trend.



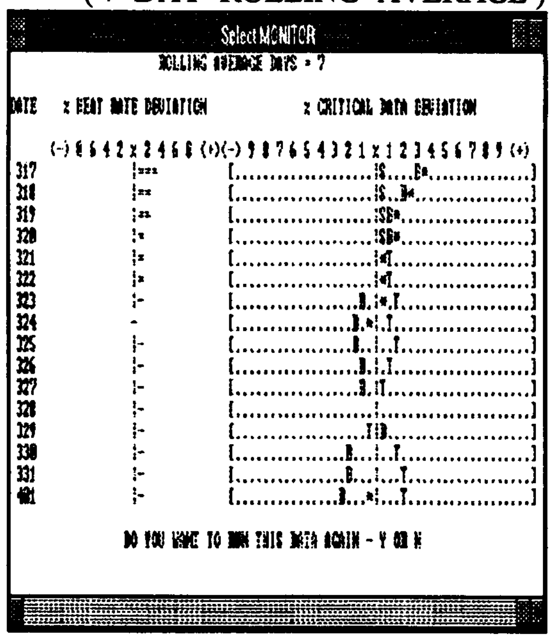
I have used this method of examining daily trends of operating heat rate as well as the ratios that define the heat rate. The resulting patterns have revealed several interesting attributes. The trend plot points I use are only for full day average operation. I have found that averaged data on days when units start up or shut down, skew the correction to standard conditions and distort the resulting deviations. I have also found that it is best to use a 5 to 7 day rolling average. This effectively removes data noise from the trend pattern, however it diminishes the resolution of the trend details. Sometimes, 2 or 3 day averages gives good resolution with sufficiently reduced data noise.

Samples of these trends are taken from a database for Ghent Unit 3 over the same time period. One trend shows data as recorded, the other shows the effect of a 7 day rolling average.

(AS RECORDED DATA)



(7 DAY ROLLING AVERAGE)



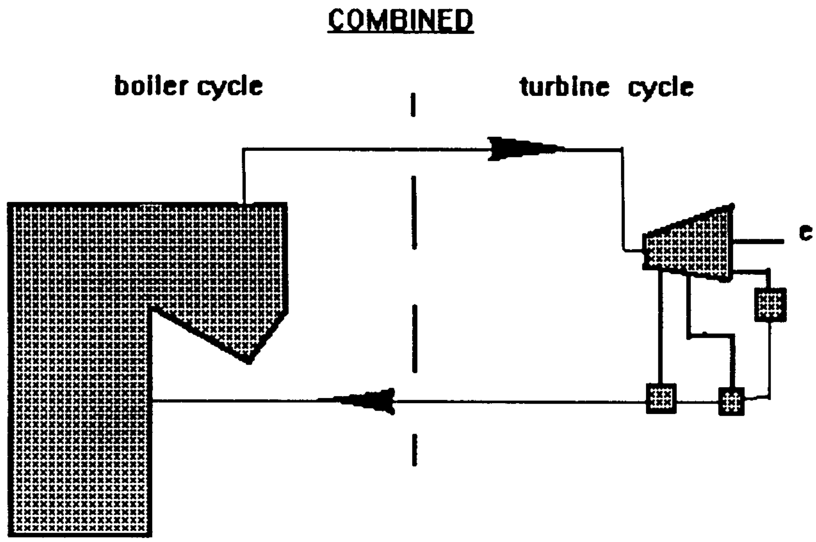
Each trend actually shows two normalized trend plots. On the far left is the month and day of each data record. To the right of the date is the percent change of heat rate from the benchmark. To the right of the heat rate trend is the composite trend of the Boiler, Turbine and Station use ratios. These values are also plotted as the percent change of their respective benchmarks. This method of presenting the data is functional in that it indicates the ratios which have influenced the changes in heat rate.

COMBINED CYCLE STUDIES

When I began to trend operating performance using ratios, I expected to see changes in heat rate correspond with a change in one of the three ratios. This seldom seemed to be the case. Frequently the turbine and boiler ratios seemed to move opposite to each other, but on some occasions they moved in unison. This led me to suspect steam flow measurement error, however that was not the cased. By correlating cycle disturbances, such as taking a high pressure feedwater heater out of service, with the corresponding ratio pattern, I realized that the turbine and boiler ratios have a unique relationship with each other and respond differently to different disturbances in the combined turbine-boiler cycle.

The ability to recognize different patterns of a ratio trend with heat rate would be a valuable diagnostic tool. Since there are only three ratios and one heat rate to trend, the number of possible combinations of diagnostics would be very limited. There was also the question of how to get the data. I could either wait for cycle disturbances to occur on operating units and note the changes in the ratio pattern; set up tests on units to emulate disturbances; or model the combined boiler - turbine cycle and run what - if cases. I opted for the computer model, since the first two options were impractical and unreliable.

The computer modeling using **PEPSE** was no simple task. The boiler cycle needed to be in design mode with active controls for firing rate, tilt position, superheat spray and drum pressure control. All heat exchangers were in design configuration. The turbine cycle was not so rigorous, however the main condenser was in HEI configuration and controls were used to adjust main steam flow to maintain constant load. Several attempts were used to place this model into envelopes, but the controls on both cycles seemed to disrupt it too much. I even attempted to make one SUPER-MODEL , but this model never converged, or a steam properties call would go out of limits on some remote iteration. One super- model run, using an IBM 4381 under VM lasted 6 hours before being bumped off line by data processing. Seems it was using too much computer resources. The end result was that each cycle had to be run separately to convergence.



Then the data manually transferred to the other cycle as input. This approach was cumbersome but effective, and it was still very time consuming. I mentioned this approach to Gene Minner of Halliburton NUS, Environmental Corporation. Gene took an interest in this approach and developed what is now Option 11 for PEPSE. Gene sent me a beta test copy, version 58F of PEPSE and in the process of BETA testing Option 11, I managed to run about 50 combined cycle cases using a newly acquired 486- 50mh PC, over a four month period. Some of these cases were repeat runs after model adjustment. All together, there were 30 identified combined cycle disturbances tabulated.

COMPUTER MODEL STUDIES

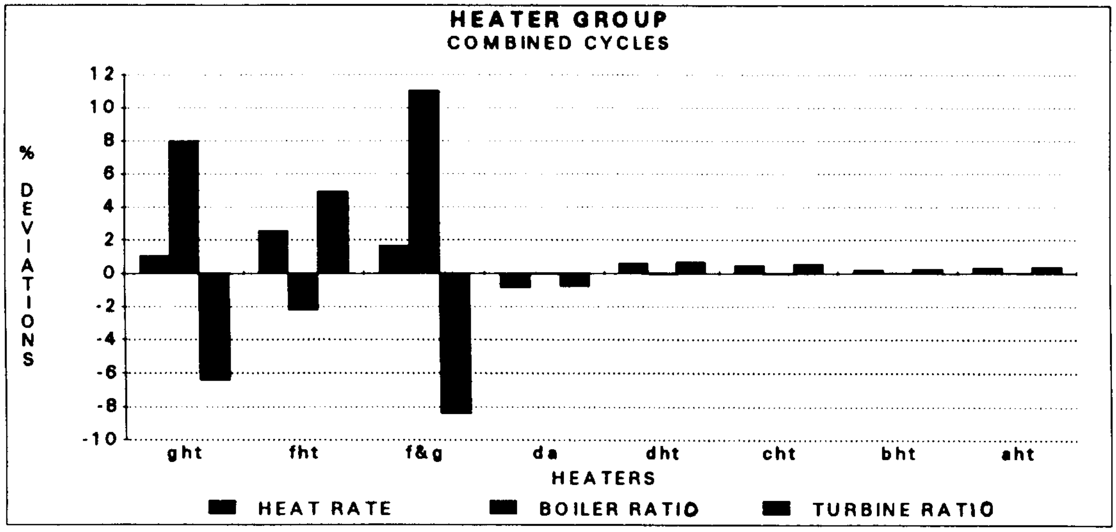
The approach used to study each disturbance was to begin with a balanced model on both boiler and turbine cycles. The balanced model I used was at full load. I then created a disturbance, such as remove a heater from service, or change a turbine stage efficiency, etc. The combined cycle was run to convergence while controlling to maintain constant load and boundary steam conditions. The resulting change in net unit heat rate as well as the corresponding ratios were noted. Below is a listing of those results.

RESULTS

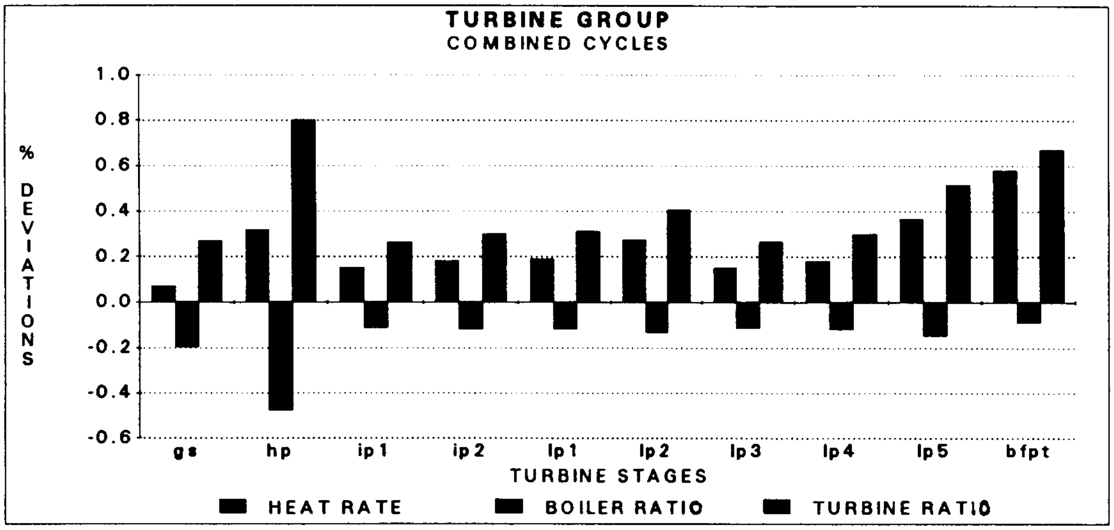
MODEL STUDIES

CASE	DESC	HR btu/nkw	HIR btu/lbstm	WR lbstm/gkw	SUR gkw/nkw
0	BASE BENCHMARK CASE	9739.02	1287.725	7.22437	1.04687
	TC HEATER GROUP				
1	G HTR OUT	9844.38	1390.89	6.76089	1.04687
2	F HTR OUT	9990.55	1259.088	7.57951	1.04687
5	F & G HTRS OUT	9901.25	1429.565	6.61598	1.04687
7	DA HTR OUT	9653.31	1286.876	7.16552	1.04687
8	LP HTR #4 OUT (D)	9798.17	1286.552	7.27487	1.04687
9	LP HTR #3 OUT (C)	9785.44	1286.79	7.26403	1.04687
10	LP HTR #2 OUT (B)	9760.65	1287.289	7.24287	1.04687
11	LP HTR #1 OUT (A)	9770.72	1287.088	7.25147	1.04687
	TURBINE GROUP				
12	GST 2% EFF. DROP	9745.95	1285.196	7.24374	1.04687
13	HPT 2% EFF. DROP	9770.04	1281.572	7.28218	1.04687
14	IP #1, 2% EFF DROP	9753.64	1286.265	7.24343	1.04687
15	IP #2, 2% EFF. DROP	9756.75	1286.202	7.24609	1.04687
16	LP #1, 2% EFF. DROP	9757.71	1286.183	7.24692	1.04687
17	LP #2, 2% EFF. DROP	9765.77	1286.021	7.25382	1.04687
18	LP #3, 2% EFF. DROP	9753.88	1286.26	7.24364	1.04687
19	LP #4, 2% EFF. DROP	9756.68	1286.204	7.24604	1.04687
20	LAST LP#5, 2%EFF. DROP	9774.84	1285.84	7.26158	1.04687
21	BFPT, 10% EFF DROP	9795.54	1286.59	7.27269	1.04687
	BOILER GROUP				
22	APC 50 DEG AIR OUT DROP	9686.56	1290.613	7.16937	1.04687
23	AH CONDUCTIVITY DROP	9806.19	1295.079	7.2329	1.04687
24	EXCESS AIR 1% INCREASE	9740.20	1286.184	7.2339	1.04687
25	INCREASE L.O.I. BY 5%	9754.07	1289.498	7.2255	1.04687
26	SUPER HEATER FOULING	9735.07	1285.355	7.23476	1.04687
27	REHEATER FOULING	9743.76	1289.756	7.21651	1.04687
28	ECONOMIZER FOULING	9747.08	1288.608	7.2254	1.04687
29	WATER WALL SLAGING	9739.34	1287.676	7.22489	1.04687
	MISC. TURBINE CYCLE GROUP				
3	N2 PACKING INC. 25%	9746.25	1286.325	7.23761	1.04687
4	N2 PACKING INC. 50%	9753.51	1284.937	7.25082	1.04687
6	CONDEN CLEAN -25%	9842.76	1285.687	7.3129	1.04687
30	TC PROCESS STEAM DUMP	9851.58	1294.052	7.27215	1.04687

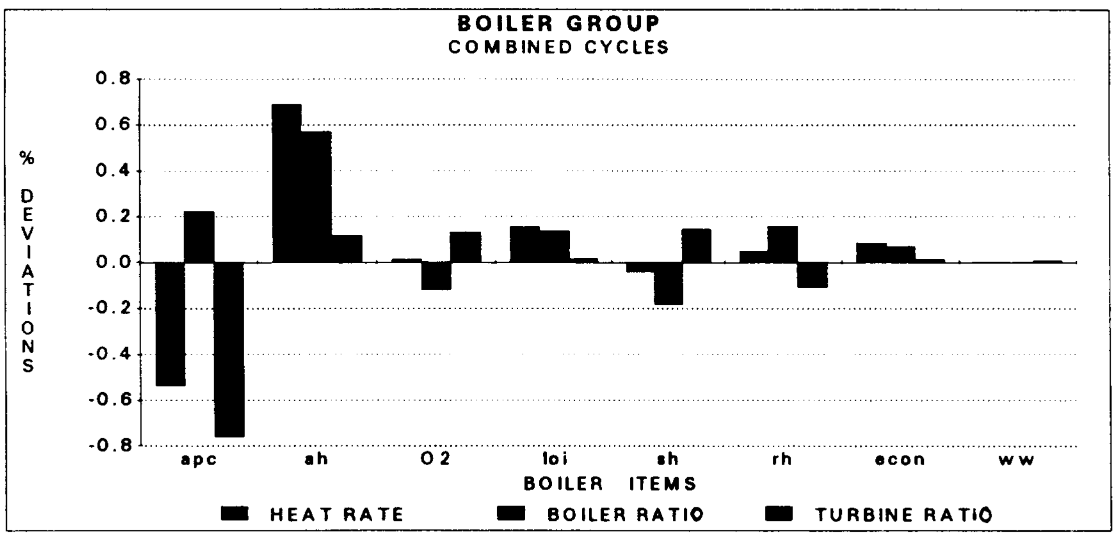
The station use ratios remained constant through all of the tests. In reality, these would change slightly from case to case, but basically the impact would be minimal. The results of these tests are graphically displayed as follows.



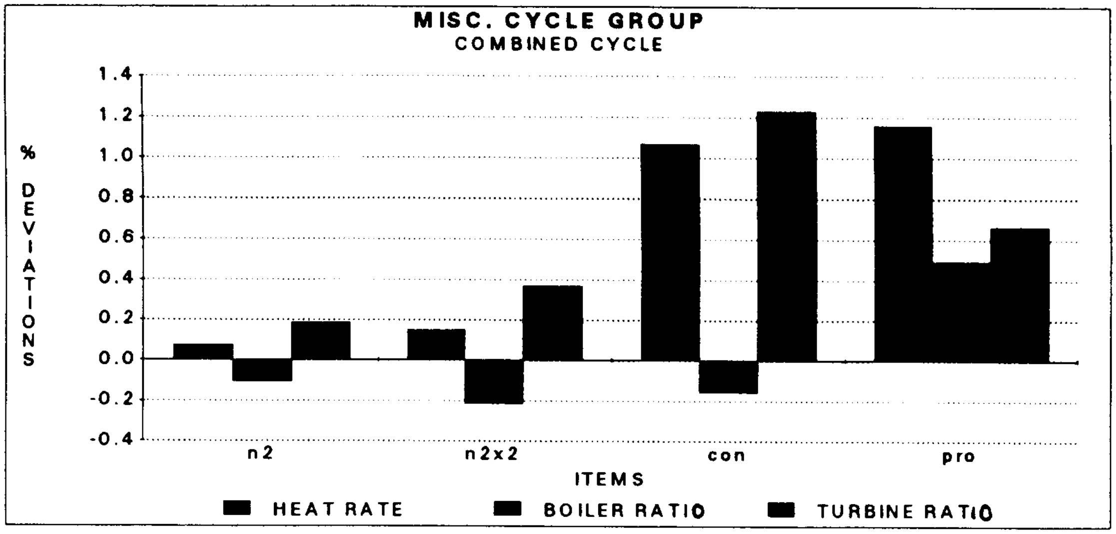
HEATER GROUP
COMBINED CYCLES
% DEVIATIONS
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
ght
fht
f&g
da
dht
cht
bht
aht
HEATERS
HEAT RATE
BOILER RATIO
TURBINE RATIO



TURBINE GROUP
COMBINED CYCLES
% DEVIATIONS
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
gs
hp
ip1
ip2
lp1
lp2
lp3
lp4
lp5
bfpt
TURBINE STAGES
HEAT RATE
BOILER RATIO
TURBINE RATIO

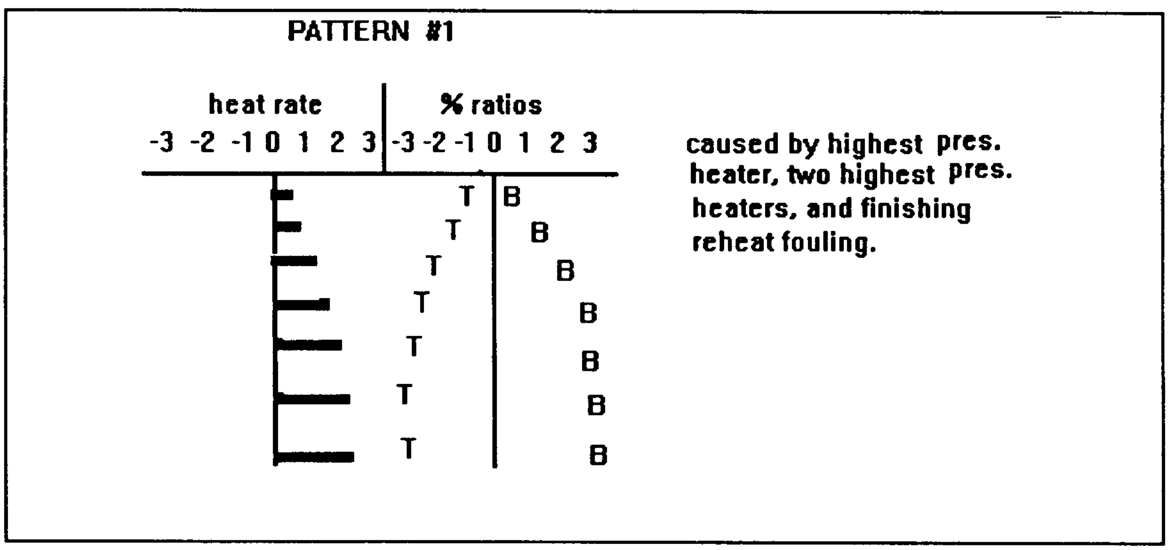


BOILER GROUP
COMBINED CYCLES
% DEVIATIONS
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
apc
ah
O2
loi
sh
rh
econ
ww
BOILER ITEMS
HEAT RATE
BOILER RATIO
TURBINE RATIO

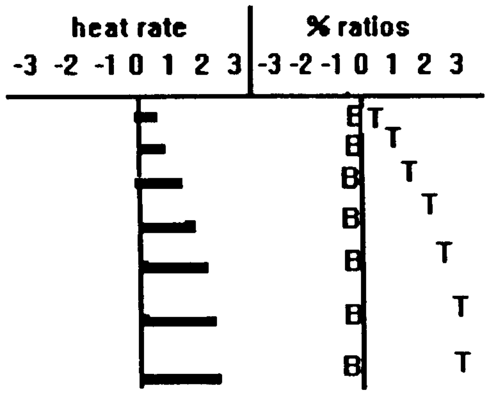


INTERPRETATION

The combined cycle studies have shown some interesting results. Altogether, there were seven distinctly different patterns, and three implied patterns useful for identifying bad data. By using the same trend format of heat rate and ratios, the pattern interpretations are as follows.

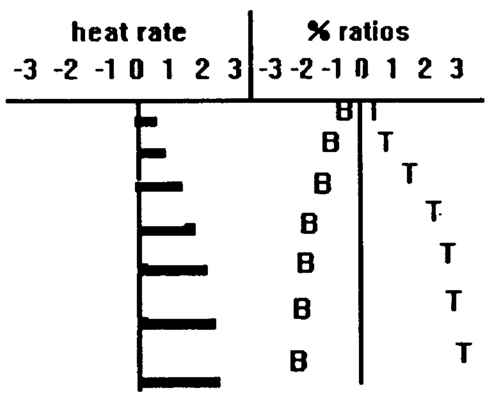


PATTERN # 2



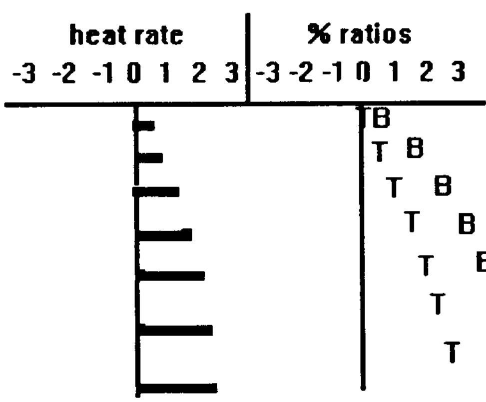
caused by low pressure feedwater heaters, small increase in heat rate.

PATTERN # 3



caused by second highest heater, turbine group, N2 packing leakage, condenser and excess air increase

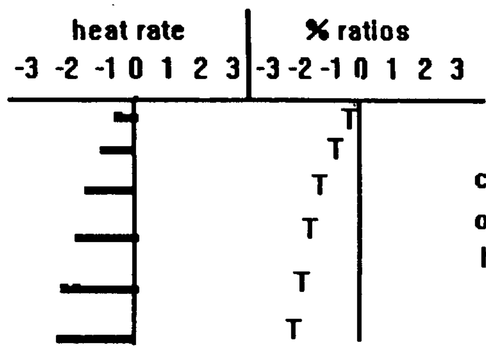
PATTERN # 4



caused by economizer fouling air heater fouling, LOI, and process steam leaving turbine cycle.

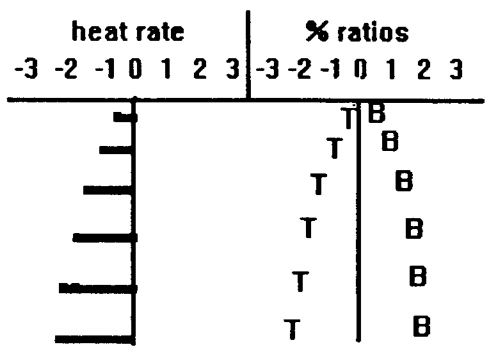
The next set of patterns I think are interesting. This represents what I would consider degradation to the combined cycle, however there was a net decrease in unit heat rate. Two of the three showed a significant decrease in heat rate.

PATTERN # 5



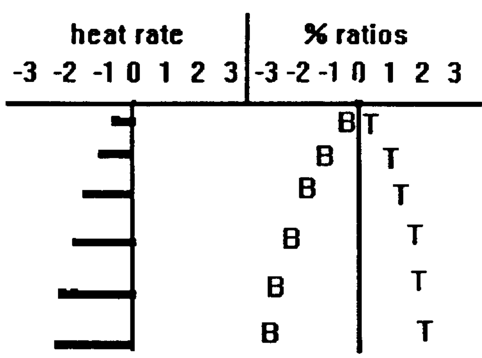
caused by taking da heater out of service. significant heat rate drop.

PATTERN # 6



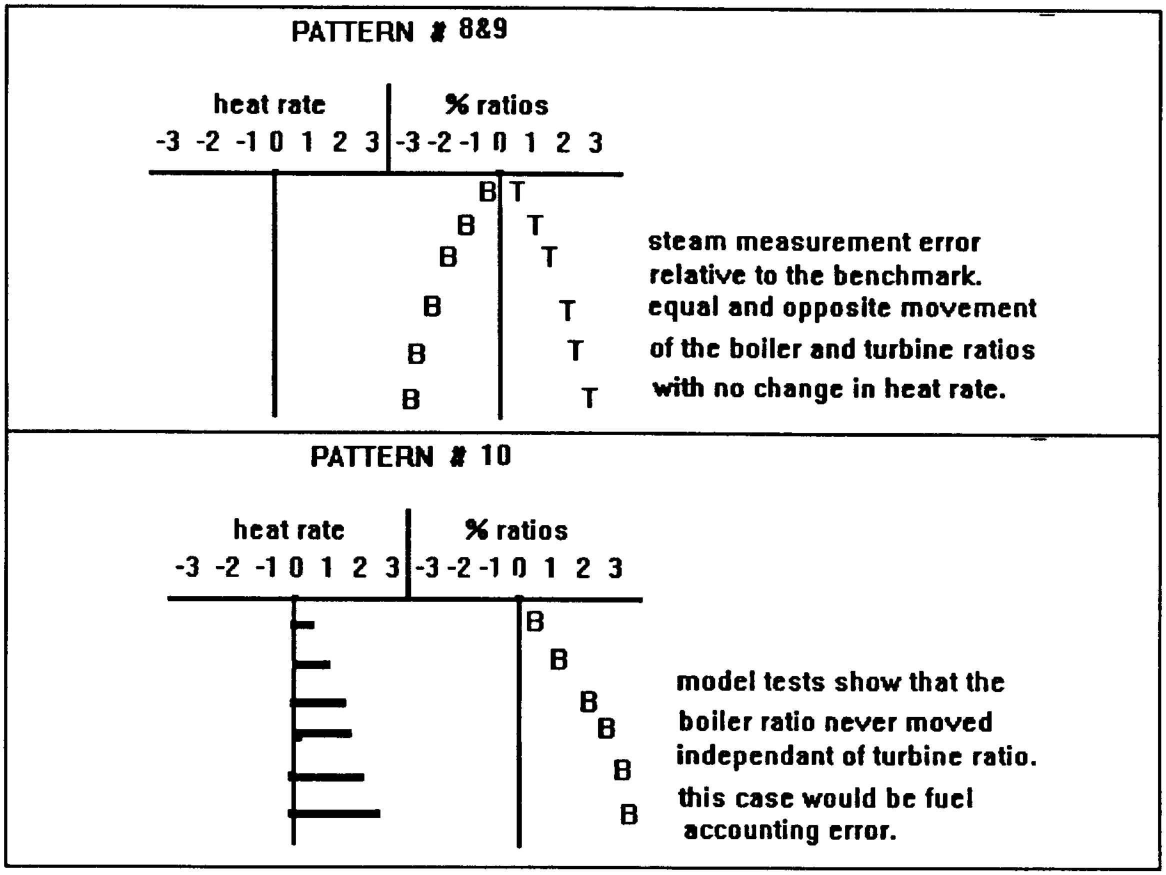
caused by decreasing air preheater coil heat exchange. significant heat rate decrease.

PATTERN # 7



finishing super heater pendant fouling. small decrease in unit heat rate.

The last set of patterns are implied . The first two represent steam measurement error high and low. There would be no net change in unit heat rate, with equal and opposite change in boiler, turbine ratios. The last pattern represents fuel accounting error. The boiler ratio will move high or low with no change in turbine ratio, and with a corresponding change in heat rate. An additional pattern would be represented by any change in heat rate due to a change in station use ratio. (intuitive)



Examples of actual operation patterns are presented in Appendix B. My experience has shown these patterns to be representative of , at least in part, real operating circumstances. I have not tested these patterns at lower then full load on the combined cycle computer model. --- time will tell.

CONCLUSION

The process of compiling/analyzing daily operating data for eleven coal fired units in the Kentucky Utilities Company has gone on now for over two years. The use of ratio analysis to diagnose general cause of heat rate change is well documented, and has proven to be a useful engineering tool. In addition, the use of the percent estimate calculation for this application has always shown reasonable results. Finally, the use of time - ratio patterns has, on several occasions, assisted in not only pinpointing the onset of a disturbance, but provided clues concerning the cause.

The value of this tool lies in the availability and simplicity of the data required. The application can be as simple as a hand calculation to compare ratios, or as sophisticated as time - pattern recognition. In all applications, some understanding of a units operating performance is obtainable, pointing in a directions of further testing, or at least questioning of unit operations.

APPENDIX

DEMONSTRATION OF ESTIMATE ERROR

(ratios)	REFERANCE	TEST	DIFFERANCE	
BOILER ————	$br := 1500.0$	$bt := 1475.0$	$db := br - bt$	
TURBINE ————	$tr := 6.0$	$tt := 6.7$	$dt := tr - tt$	
STATION USE ——	$sr := 1.0668$	$st := 1.064$	$ds := sr - st$	
	$hr := br \cdot tr \cdot sr$	$ht := bt \cdot tt \cdot st$	$dh := hr - ht$	
HEAT RATE ———	$hr = 9601.2$	$ht = 10514.98$	$dh = -913.78$	TARGET VALUE

==

DEVIATION ESTIMATE

$dh1 := (br + db) \cdot (tr + dt) \cdot (sr + ds) - br \cdot tr \cdot sr$

$dh1 = -956.158$

$$\% \text{ error} = \frac{dh - dh1}{dh} \cdot 100 = -4.638$$

PERCENT ESTIMATE

$$dh2 := \left(\frac{db}{br} + \frac{dt}{tr} + \frac{ds}{sr} \right) \cdot hr$$

$dh2 = -934.92$

$$\% \text{ error} = \frac{dh - dh2}{dh} \cdot 100 = -2.313$$

==

DEMONSTRATION OF ESTIMATE ERROR FROM SAMPLE APPLICATION

	GHENT 4	GHENT 3	DIFFERANCE	
REPORTED NUHR	9970.93	10574.13	603.2	
(ratios)				
BOILER ————	$br := 1434.796$	$bt := 1585.367$	$db := br - bt$	
TURBINE ————	$tr := 6.528$	$tt := 6.176$	$dt := tr - tt$	
STATION USE ——	$sr := 1.06455$	$st := 1.07996$	$ds := sr - st$	
	$hr := br \cdot tr \cdot sr$	$ht := bt \cdot tt \cdot st$	$dh := hr - ht$	
HEAT RATE ———	$hr = 9970.95$	$ht = 10574.13$	$dh = -603.19$	TARGET VALUE

==

DEVIATION ESTIMATE

$dh1 := (br + db) \cdot (tr + dt) \cdot (sr + ds) - br \cdot tr \cdot sr$

$dh1 = -701.303$

$$\% \text{ error} = \frac{dh - dh1}{dh} \cdot 100 = -16.266$$

PERCENT ESTIMATE

$$dh2 := \left(\frac{db}{br} + \frac{dt}{tr} + \frac{ds}{sr} \right) \cdot hr$$

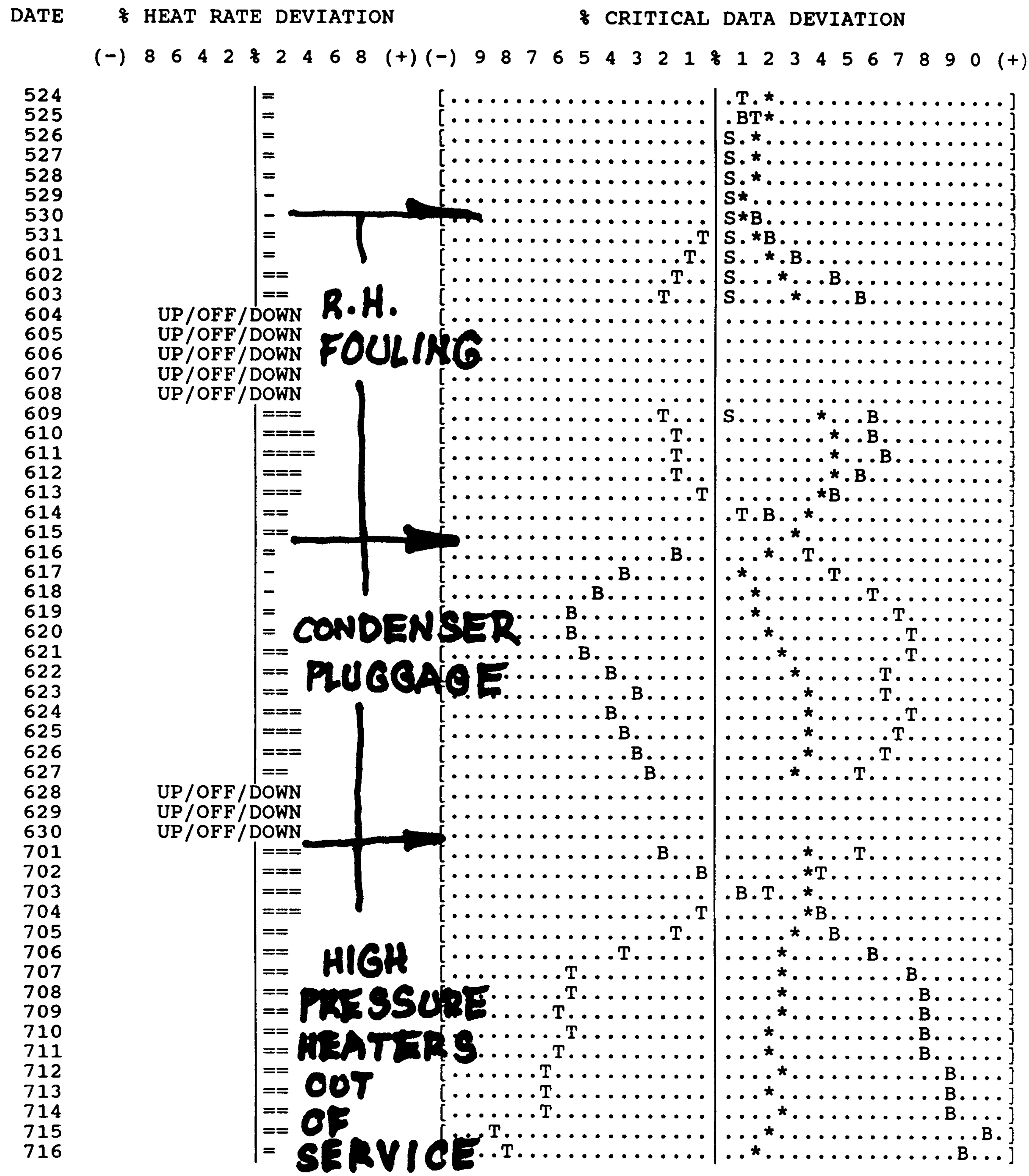
$dh2 = -653.062$

$$\% \text{ error} = \frac{dh - dh2}{dh} \cdot 100 = -8.269$$

APP. (B)

CRITICAL DATA TREND FOR GHENT 1 1991

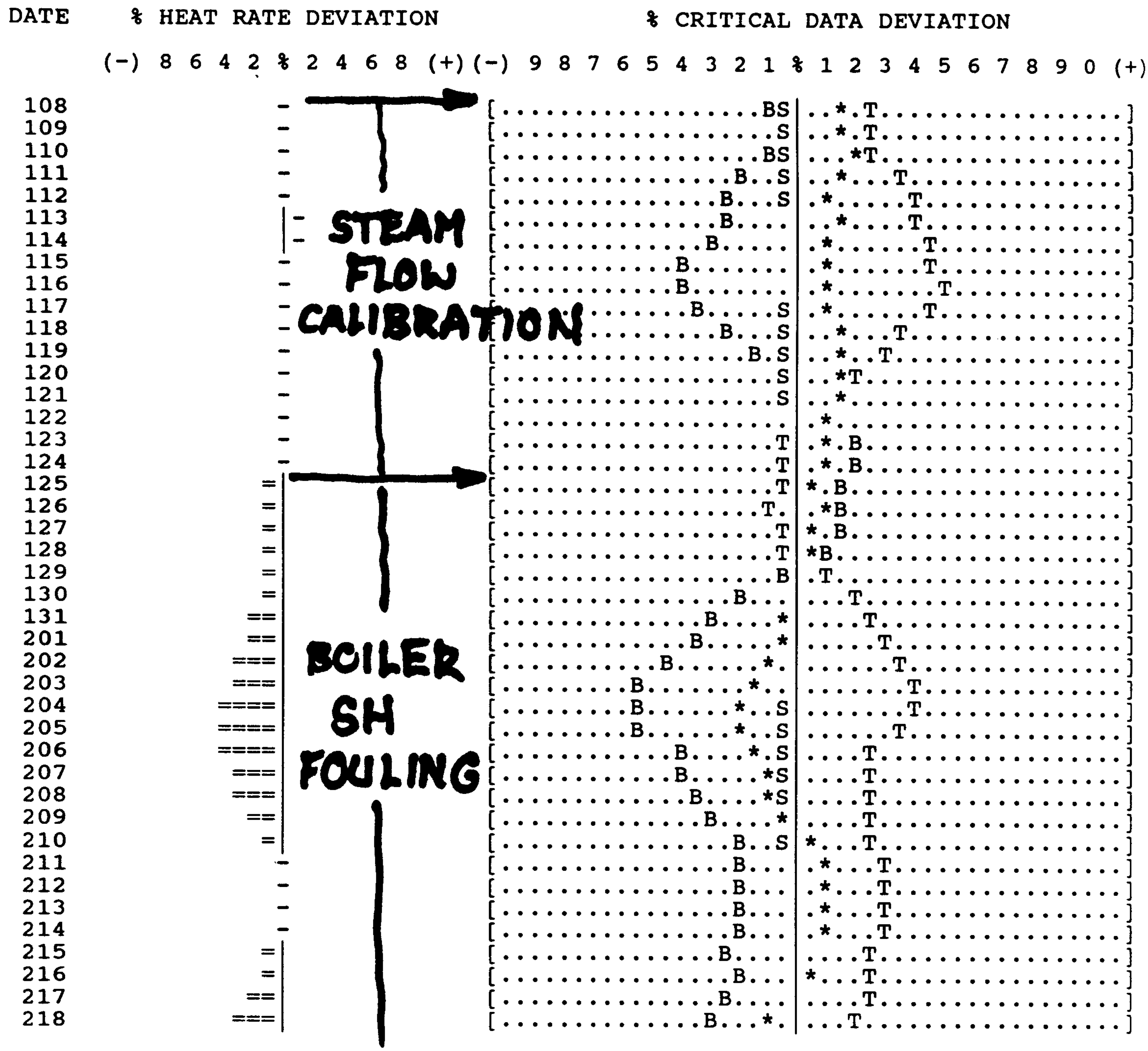
ROLLING AVERAGE DAYS = 7



APP. (B)

CRITICAL DATA TREND FOR GHENT 4 1992

ROLLING AVERAGE DAYS = 7



APP. (B)

CRITICAL DATA TREND FOR GHENT 1 1992

ROLLING AVERAGE DAYS = 7

```
DATE      % HEAT RATE DEVIATION              % CRITICAL DATA DEVIATION

      (-) 8 6 4 2 % 2 4 6 8 (+)(-) 9 8 7 6 5 4 3 2 1 % 1 2 3 4 5 6 7 8 9 0 (+)

1117            |=            [....................|T.B*..................]
1118            |=            [....................|T.B*..................]
1119            |=            [....................|...*..................]
1120            |=            [....................|..*...................]
1121            |-            [....................|..*...................]
1122            |-            [...................T|..*B..................]
1123            |=            [...................T|...*.B................]
1124            |=            [..................T.|....*B................]
1125            |=            [..................T.|...*.B................]
1126            |=            [...................T|...*B.................]
1127            |=            [...................T|....*B................]
1128            |=            [...................T|....*B................]
1129            |=            [...................T|....*B................]
1130            |=            [...................T|...*B.................]
1201            |-            [...................T|..*B..................]
1202            |=            [...................T|...*..................]
1203            |=            [....................|...*B.................]
1204            |==           [................T...|....*...B.............]
1205            |==           [.....T..............|.*..............B.....]
1206            |===          [...T................|.*................B...]
1207            |===          [...T................|.*................B...]
1208            |===          [..T.................|..*.................B.]
1209            |===          [..T.................|.*..................B.]
1210            |===          [.T..................|.*..................B.]
1211            |==           [...T................|*................B....]
1212            |=            [..............T.....|...*....B.............]
1213            |=            [...............T....|...*...B..............]
1214            |-            [...............T....|..*....B..............]
1215            |-            [...............T....|.*....B...............]
1216            |-            [...............T....|.*.....B..............]
1217            |-            [..............T.....|.*.....B..............]
1218            |-            [..............T.....|..*....B..............]
1219            |-            [..............T.....|..*.....B.............]
1220            |-            [..............T.....|.*......B.............]
1221            |=            [..............T.....|..*......B............]
1222            |=            [..............T.....|...*.....B............]
1223            |=            [..............T.....|..*......B............]
1224            |=            [...............T....|...*....B.............]
1225            |=            [.................T..|...*..B...............]
1226            |-            [..................T.|..*.B.................]
1227            |-            [...................T|..*B..................]
1228            |-            [...................T|.*B...................]
1229            |-            [....................|..*...................]
1230            |-            [....................|.B*...................]
```

HP HEATERS OUT OF SERVICE

APP. (B)

CRITICAL DATA TREND FOR GHENT 3 1993

ROLLING AVERAGE DAYS = 7

```
DATE     % HEAT RATE DEVIATION              % CRITICAL DATA DEVIATION

       (-) 8 6 4 2 % 2 4 6 8 (+)(-) 9 8 7 6 5 4 3 2 1 % 1 2 3 4 5 6 7 8 9 0 (+)

 921                 |-          [...................B|*T....................]
 922                 |-          [...................B|S.....................]
 923                 |-          [..................B*|S.....................]
 924                 |-          [...................*|S.....................]
 925                 |-          [...................*|S.....................]
 926                  -          [..................*B|S.....................]
 927                  -          [..................T*|S.....................]
 928                 |-          [.....T..........*...|S..........B..........]
 929                 |-          [.......T.........*..|S........B............]
 930                 |=          [......T..........*..|S.........B...........]
1001                 |-          [......T.........*...|S........B............]
1002                 |-          [.......T.......*....|S.......B.............]
1003                 |-          [......T.........*...|S........B............]
1004                 |-          [......T.........*...|S........B............]
1005                 |-          [...................*|S.....................]
1006                 |-          [...................T|S.....................]
1007                  -          [...................*|S.....................]
1008                  -          [...................*|S.....................]
1009                 |-          [..................B*|S.....................]
1010                 |-          [..................B*|ST....................]
1011                 |-          [.................B.*|ST....................]
1012                  -          [.................B.*|ST....................]
1013                 |-          [..................B*|S.....................]
1014                 |-          [.................B.*|ST....................]
1015                  -          [.................B*.|S.....................]
1016                =|           [.................*BT|S.....................]
1017                =|           [...............*....|S.....................]
1018                =|           [................*...|S.....................]
1019                =|           [................*...|S.....................]
1020                  -          [................T*..|S.....................]
1021                  -          [.................*..|S.....................]
1022                  -          [..................*.|S.....................]
1023                 |-          [..................T*|S.....................]
1024                 |=          [....................|S*....................]
1025                 |=          [....................|S*....................]
1026                 |=          [....................|ST*...................]
1027                 |=          [....................|S*....................]
1028                 |=          [....................|S*....................]
1029                 |=          [....................|S.*...................]
1030                 |=          [....................|S*....................]
1031                 |=          [....................|S*....................]
1101                 |-          [....................|S.....................]
1102                 |-          [.................T..|S.B...................]
1103                 |-          [..............T.....|S....B................]
1104                 |-          [..............T....*|S...B.................]
1105                 |-          [.............T.....*|S....B................]
1106                 |-          [............T.......|S......B..............]
1107                 |=          [............T.......|S.......B.............]
1108                 |=          [............T.......|S*.......B............]
1109                 |=          [...............T....|*....B................]
1110                 |=          [..................T.|S*.B..................]
1111        UP/OFF/DOWN          [....................|......................]
1112        UP/OFF/DOWN          [....................|......................]
1113        UP/OFF/DOWN          [....................|......................]
```

NOISE (NORMAL) — 921–927

PLANT DATA ERROR — 928–1004

NOISE (NORMAL) — 1016–1022

STEAM FLOW ERROR ΔP — 1101–1110

APP. (B)

CRITICAL DATA TREND FOR GHENT 3 1992

ROLLING AVERAGE DAYS = 7

```
DATE     % HEAT RATE DEVIATION            % CRITICAL DATA DEVIATION

     (-) 8 6 4 2 % 2 4 6 8 (+)(-) 9 8 7 6 5 4 3 2 1 % 1 2 3 4 5 6 7 8 9 0 (+)

213             |-      [...................T|*.B...................]
214             |-      [...................T|.*B...................]
215             |-      [..................T.|*B....................]
216             |-      [...................T|*.B...................]
217             |-      [..................T.|*.B...................]
218             |-      [..................T.|*.B...................]
219             |-      [..................T.|*B....................]
220             |-      [...................T|B.....................]
221             |-      [...................T|B.....................]
222             |-      [...................T|*B....................]
223             |-      [...................T|B.....................]
224             |-      [....................|S.....................]
225             |=      [....................|S*....................]
226             |=      [....................|S.*...................]
227             |==     [....................|S..*..................]
228             |==     [....................|S..B*.................]
229             |===    [....................|S....*................]
301             |====   [....................|S.....*...............]
302             |====   [....................|S......*..............]
303             |====   [...................T|S......*B.............]
304             |====   [...................T|S.....*B..............]
305             |===    [....................|S.....*...............]
306             |===    [...................T|S....*B...............]
307             |===    [...................T|S....*B...............]
308             |===    [...................T|S....*B...............]
309             |===    [....................|S....*................]
310             |===    [....................|S....B*...............]
311             |===    [....................|S.....*...............]
312             |====   [....................|S.....B*..............]
313             |====   [....................|S......*..............]
314             |====   [....................|S.....*...............]
315             |===    [....................|S....B*...............]
316             |===    [....................|S....B*...............]
317             |==     [....................|S...*.................]
318             |==     [....................|S.*B..................]
319             |=      [....................|S*....................]
320             |=      [....................|S*....................]
321             |-      [...................B|*.....................]
322             |-      [...................B|.T....................]
323            -|       [.................B.*|.T....................]
324            -|       [.................B.*|.T....................]
325             |-      [.................B..|..T...................]
326             |-      [..................B.|.T....................]
327             |-      [..................B.|T.....................]
328             |-      [....................|......................]
329             |-      [...................T|B.....................]
330             |-      [................B...|..T...................]
331             |-      [................B...|...T..................]
401             |-      [...............B...*|...T..................]
402             |-      [..............B....*|S..T..................]
403            -|       [..............B...*.|S..T..................]
404            -|       [.............B....*.|S...T.................]
405            -|       [.............B....*.|S...T.................]
406            -|       [..................B*|T.....................]
```

NOISE (NORMAL)

FEEDER CALIBRATION (FUEL ERROR)

NOISE (NORMAL)