On Superposition of Steam Turbine Cycle Performance Correction Curves

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On Superposition of Steam Turbine Correction Factors

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Abstract

Understanding the current performance of a steam turbine cycle requires testing the system and comparing the current performance against a standard or best-achievable performance. In order to make such a comparison valid, it is necessary that the current test and the benchmark be subjected to the same boundary conditions. Main steam, reheat, and condenser conditions are such boundaries. In general it is not possible to attain an exact match of all these conditions when setting up a test. To be able to make the comparison, it is necessary to "correct" the tested performance to the standard boundary conditions, or vice versa.

It is common practice to use correction factors to account for off-normal values of several of these boundary parameters to adjust generation and heat rate values found in performance tests. This paper addresses the impact of combining several of these correction factors. In particular, we address the question, "how good are the results of superposing several effects in this way?" We address this question by running several analyses using the PEPSE heat balance program.

Introduction

When a turbine test is performed, it is generally not possible to obtain a precise match between the tested cycle boundary conditions and the "standard" boundary conditions. Since it is the objective of the test to measure the current performance of the turbines, and since off-normal values of the boundary conditions can bias/sway/skew the conclusions, it is desirable to be able to answer the question, "How would the system have performed if we had been able to match the boundary conditions?" We can answer this question by "correcting" the as-tested performance parameters. Corrections account for the offset of the values of the boundary conditions to predict the performance parameters as though the system had actually been tested at the design boundary conditions. The amount of the correction depends on how far the conditions are offset.

When a turbine vendor delivers his system, he provides "correction curves" to the customer to be used in this correction process. For example, there are curves of correction factors for turbine generation and heat rate as a function of main steam temperature. These curves are used by entering the amount of the offset of the temperature and obtaining the factor. Then the as-tested performance parameter is "corrected" by using this factor. Similar corrections are made for other parameters, such as main steam pressure, reheat temperature, reheat pressure drop, and condenser pressure.

When the vendor developed these correction curves, he did so as single-effects for the system. The other boundary conditions were held fixed while a single boundary condition was varied through a range of values. When we apply them in the fashion described, the effects are no longer separate and independent, or are they? It is the intent of this study to answer this question.

We may anticipate that as long as the offsets are "small", the corrections can be combined with reasonable accuracy. How small is small?

Method of Analysis

In order to make the results self-consistent, the analysis method of this paper has not used any vendor correction curves (a few spot checks against vendor correction curves have been made to build confidence in the results[Reference 1]. Instead of analyzing via vendor curves, we have used a heat balance program, PEPSE, to analyze the question. PEPSE does not contain correction curves. Instead, PEPSE contains generalized representations of individual component performance over the load range. PEPSE accurately predicts the consequences of variations of any number of conditions or operating parameters of the system[Reference 2 and 3].

The first step of these analysis tasks has been to determine the performance impact of offset of parameters as single effects. To do this, a "typical" fossil single reheat steam turbine cycle model has been selected for the studies. This is a 650 mW unit. By design, it operates at 2414 psia, 1000F main steam, 1000F hot reheat, 10% reheat pressure drop, and 2.5 in.Hg condenser pressure. Figure 1 shows the PEPSE model schematic for this system.

Several sensitivity studies have been run, wherein each of these parameters has been varied, one at a time, step-wise over a range of values to calculate the generation and heat rate of the system. The raw results have been plotted, and they are presented as Figures 2 through 11. Note that the runs were made with PEPSE's Special Option 1 active. This option adjusts the main steam flow to be consistent with the flow passing ability of the control valves and governing system as the main steam temperature and/or pressure are varied.

The next step was to run a few analyses wherein offsets of all of the parameters were combined. The values of the calculated generation and heat rate were observed. The design point and combinations that included the same offsets for all of the other parameters were run as had been run in the single-effect sensitivity studies. For clarification of this point, compare Table 6A with Tables 1 through 5.

The raw results are provided in Tables 1-6. The percent deviation from design at valves-wide-open for power and gross heat rate are also presented in these tables. To compare these combined results against superposition, the single-effect deltas of gross power and gross heat rate were added. The results from the two different approaches are provided in Table 6A and 6B for combined analysis and superposed analysis, respectively. Table 7A, 7B, and 7C summarize these results.

To verify that the results of the individual cases were behaving in an expected manner, PEPSE's results were compared to the "rule of thumb" expected behavior, based on Reference 3. To summarize these rules, the following general characteristics would be expected:

1. An increase in throttle temperature of 50 F decreases the load by 0.3%. The flow decreases 1.7%. As throttle temperature increases the available energy increases, providing the turbine the opportunity to increase output. Also the decrease in flow reduces the total exhaust loss, which improves the LP efficiency.

2. An increase in throttle pressure of 5% increases flow approximately 5%, but the load increases only approximately 4.7%. This difference is due to increased exhaust loss which increases the LP turbine UEEP reducing the power of the LP Turbine. The throttle available energy is greater at 5% greater pressure.

3. A 50 F increase in reheat temperature increases output by 2.3 % at rated load,. By comparison, an increase in throttle temperature decreases load because the flow is reduced due to lower density. Changes in throttle temperature affect flow, whereas reheat has a negligible effect on flow.

4. A 5% increase in reheat pressure drop results in increasing the HP turbine exhaust pressure by 5%. About one-third of the power is produced in the HP turbine at rated load. Thus the load would be reduced by about 1.15% for a 5% increase in reheat pressure drop. In addition, the higher HP turbine exhaust pressure increases the feedwater heater pressure, resulting in more extraction flow to the heater and less flow through the IP and LP turbines. The combination of these effects decreases the load by 1.4% at rated load.

5. The effect on heat rate is as follows. The higher HP exhaust temperature decreases the amount of energy added in the reheater. The rule of thumb is that a 1% increase in pressure drop gives a 0.1% poorer heat rate.

The base case full load power is 657 MW and the gross heat rate is 7880 BTU/KWH. As shown in Figure 2, the power decreased as the throttle temperature increased. Figure 5 shows an increase in power as the pressure is increased, as predicted in number 2 above. Figure 7 is consistent with number 3 above and number 4 and 5 are consistent with Figure 8 and 9, respectively.

A specific pattern of boundary condition offsets was chosen in performing the combined offset analyses. The boundary conditions were taken up or taken down, as a group, simultaneously. For example, the full-range case - case #105 - had main steam temperature and pressure at the minimums of their respective ranges and the other boundary conditions at the minimums of their ranges. It would be an easy matter to combine the offsets in a different scheme. It is our judgment that the conclusions of the study would have been similar to those that have been drawn using the stated pattern.

Calculations

The standard approach for "correcting" as-tested generation or heat rate for the offset of a single boundary condition is to use an equation of the form

PP(corrected) = PP(measured) / correction factor,

Where

PP = performance parameter (either generation or heat rate)

Correction factor = a fractional value obtained by use of vendor's correction curves as a function of the offset of the single boundary condition.

When more than one of the boundary conditions in a test is offset from the standard value, the equation above is applied individually, one-at-a-time (or else a combined correction factor is formed) to obtain the overall "superposed" correction for all of the offsets.

This correction process could be viewed in an alternative way, as follows: a single correction could be considered

PP(corrected) = PP(measured) + DELTA

Where DELTA is the difference between the as-tested and the at-standard performance parameter value. The results of the parameter sensitivity studies have been presented in the form of these DELTA's, as shown in Figures 2 through 11. The superposition results have been obtained by using the correction formula in the additive form shown above. There is no need to convert the results into the more familiar correction factor that is used as a divisor.

Results

Figures 2 through 11 show the single-effect deviations. Tables 6 and 7 detail the overall deviations of generation and heat rate that were calculated by superposing the single-effect corrections, as well as the deviation of these performance parameters that were determined by running PEPSE with all of the offsets combined in a single heat balance analysis.

The tables show that, when the boundary conditions are only slightly offset from design values, heat rate and generation are calculated well by superposing single-effect corrections, see Cases 102 and 104 in Tables 6 and 7. As the offsets become larger, up to the full-range offsets, the deviation between the true combined effect results and the superposed corrections becomes larger, as shown in Cases 101 and 105 in Tables 6 and 7.

PEPSE's "corrections" were compared with the vendor's correction curves at the extremes of each one of the boundary condition ranges. This was performed with each boundary condition offset as a single effect. The results are provided in footnotes in Tables 1-5. The comparison between PEPSE results and the vendor's predictions are reasonable, but not exact. These observations have been made in previous work.[1] The purpose of the comparison was to both analyze the results and verify the accuracy of the analyses performed with PEPSE. The single effects are expected to be reasonably accurate.

Figure 1 PEPSE MODEL

FOSS TG CYCLE - BASE (DESIGN)

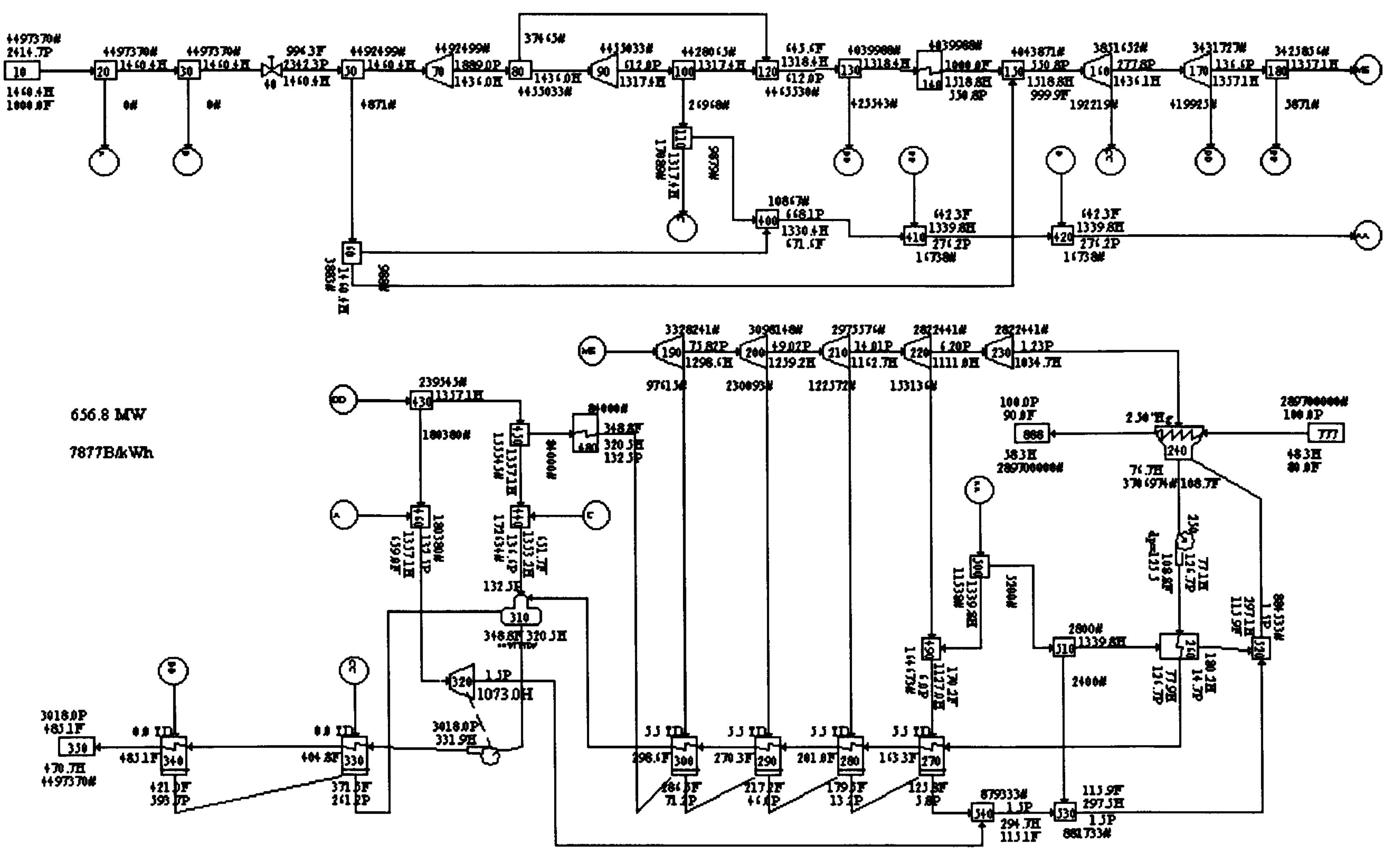

Figure 2 Gross Heat Rate as a Function of Main Steam Temperature

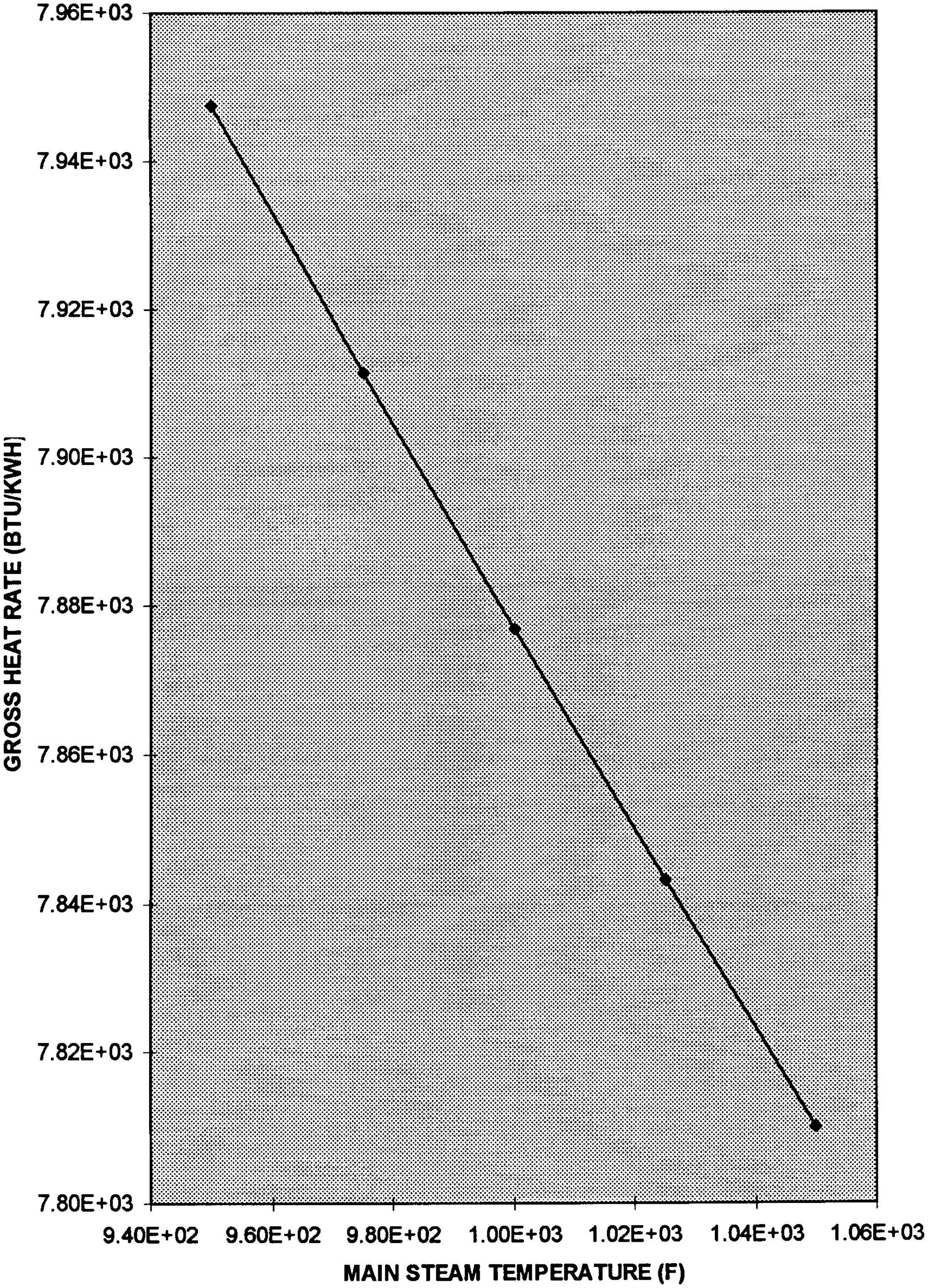

Figure 3 Gross Power as a Function of Main Steam Temperature

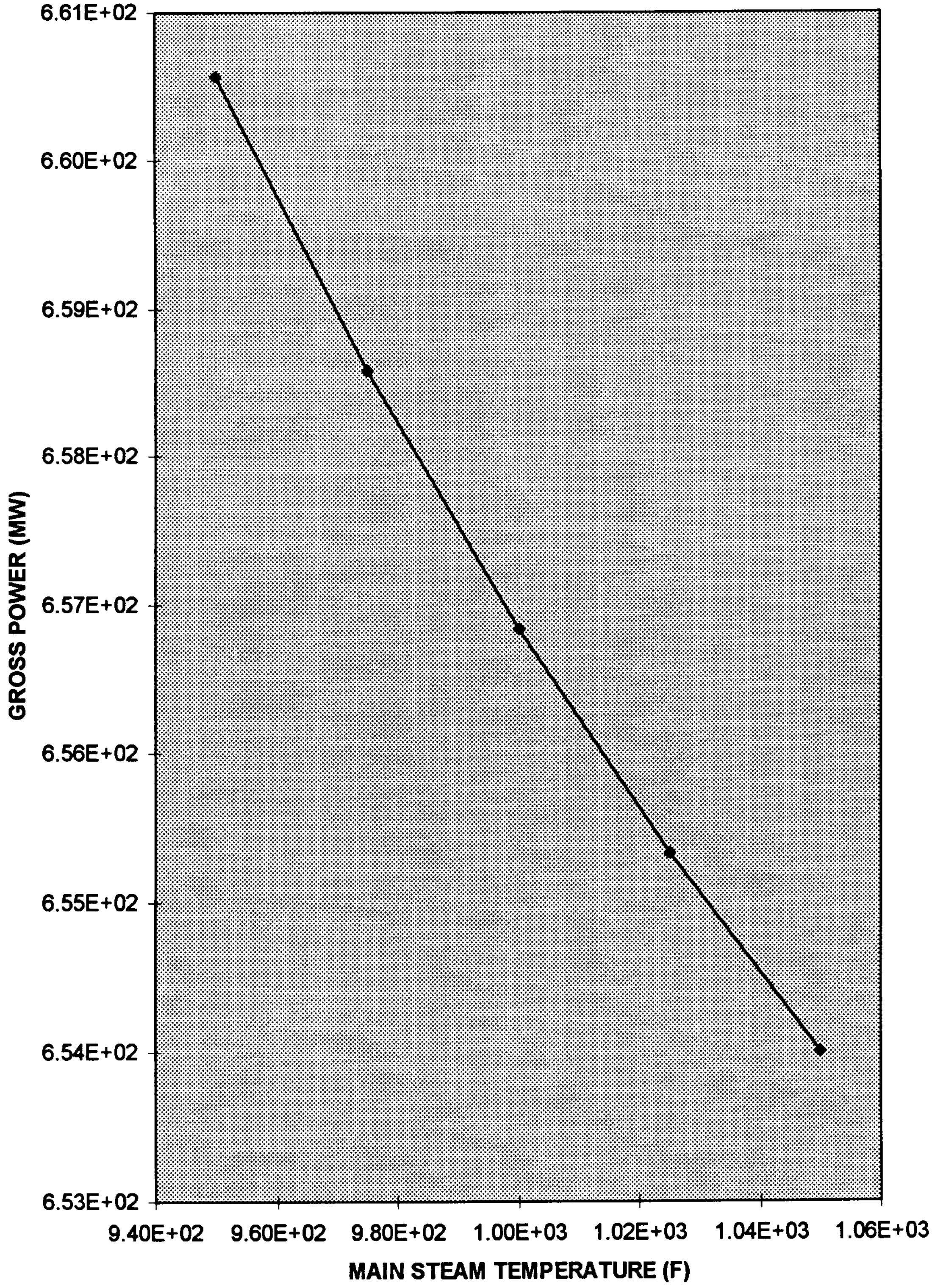

Figure 4 Gross Heat Rate as a Function of Main Steam Pressure

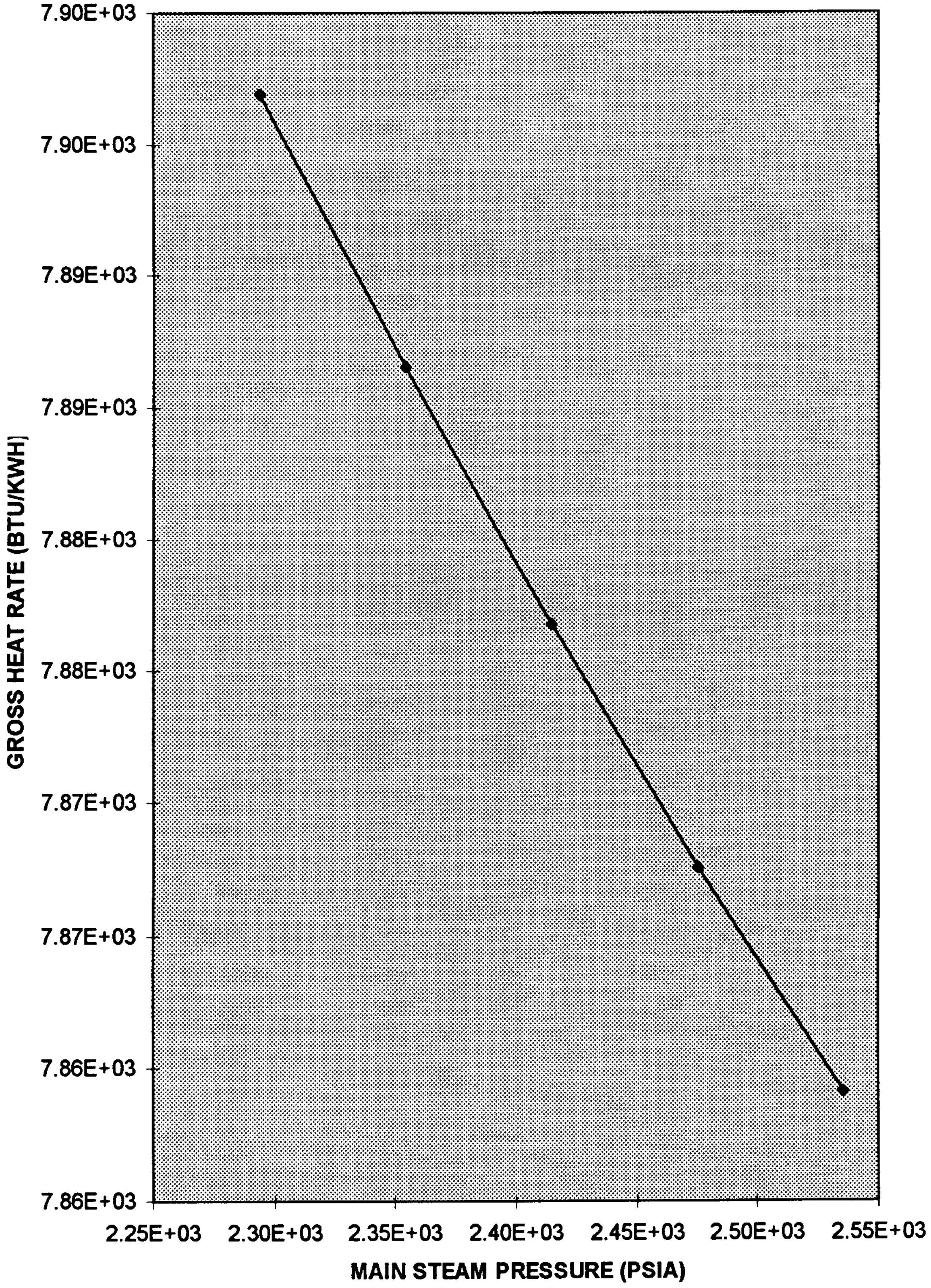

Figure 5 Gross Power as a Function of Main Steam Pressure

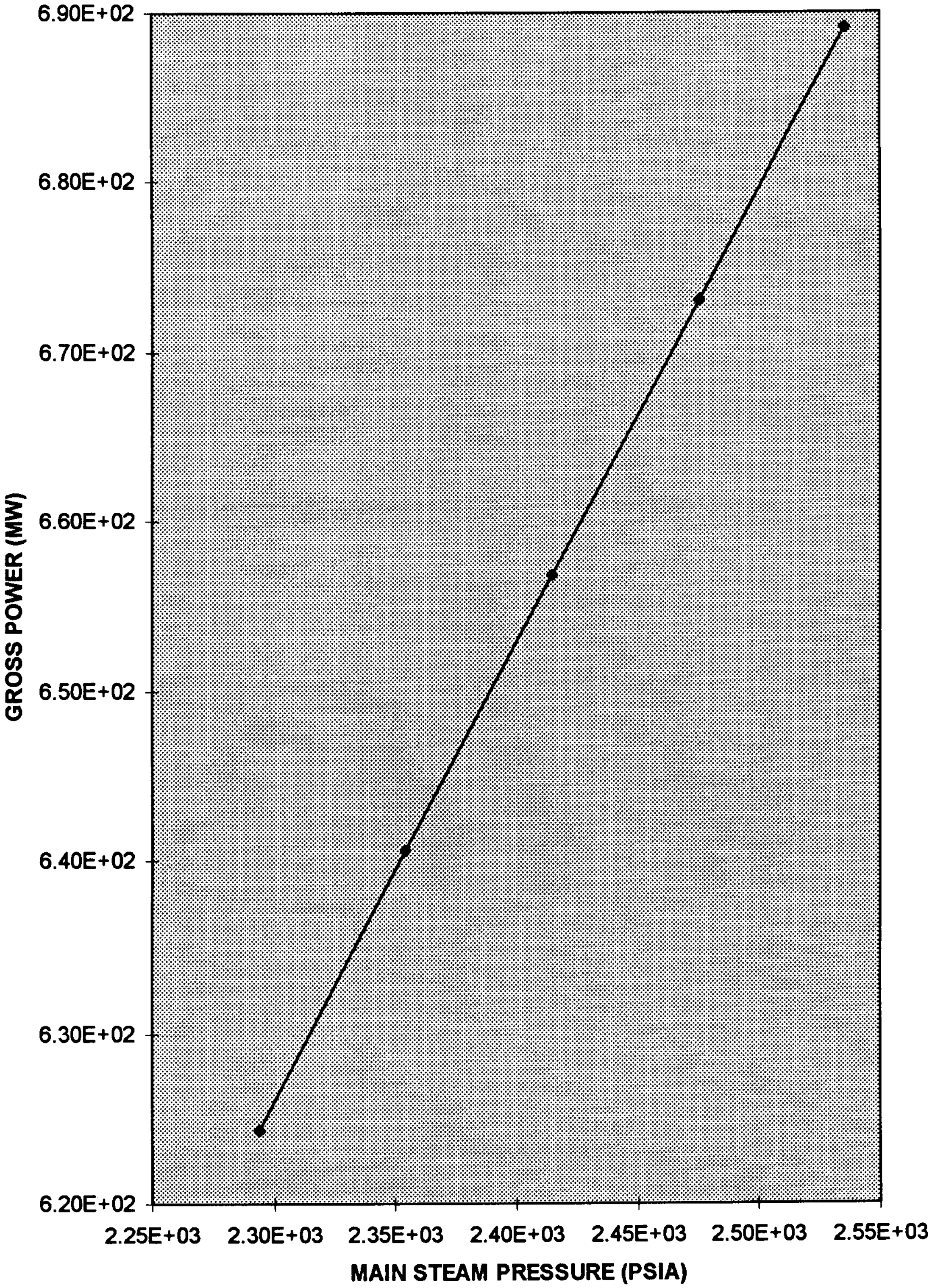

Figure 6 Gross Heat Rate as a Function of Reheat Temperature

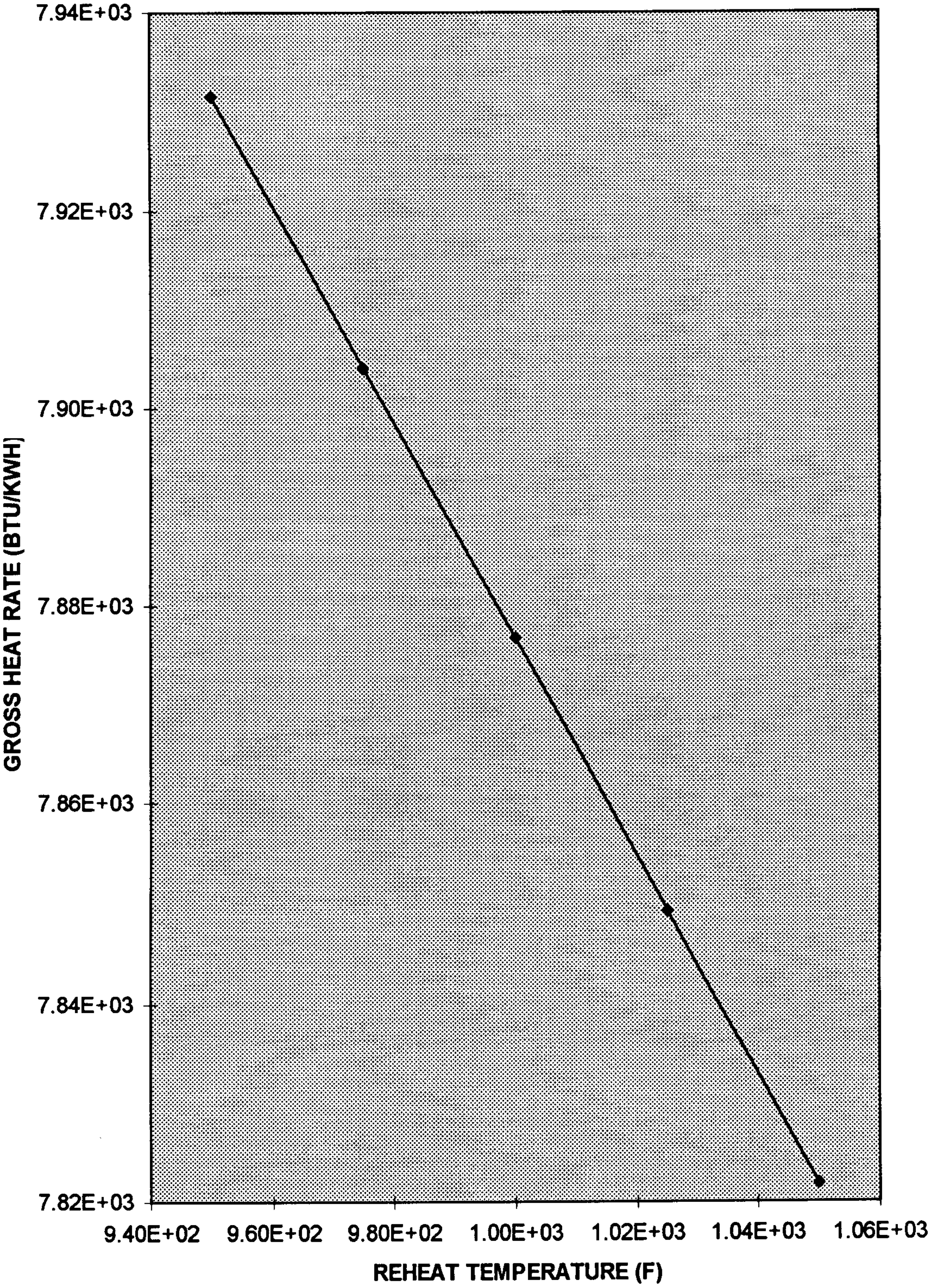

Figure 7 Gross Power as a Function of Reheat Temperature

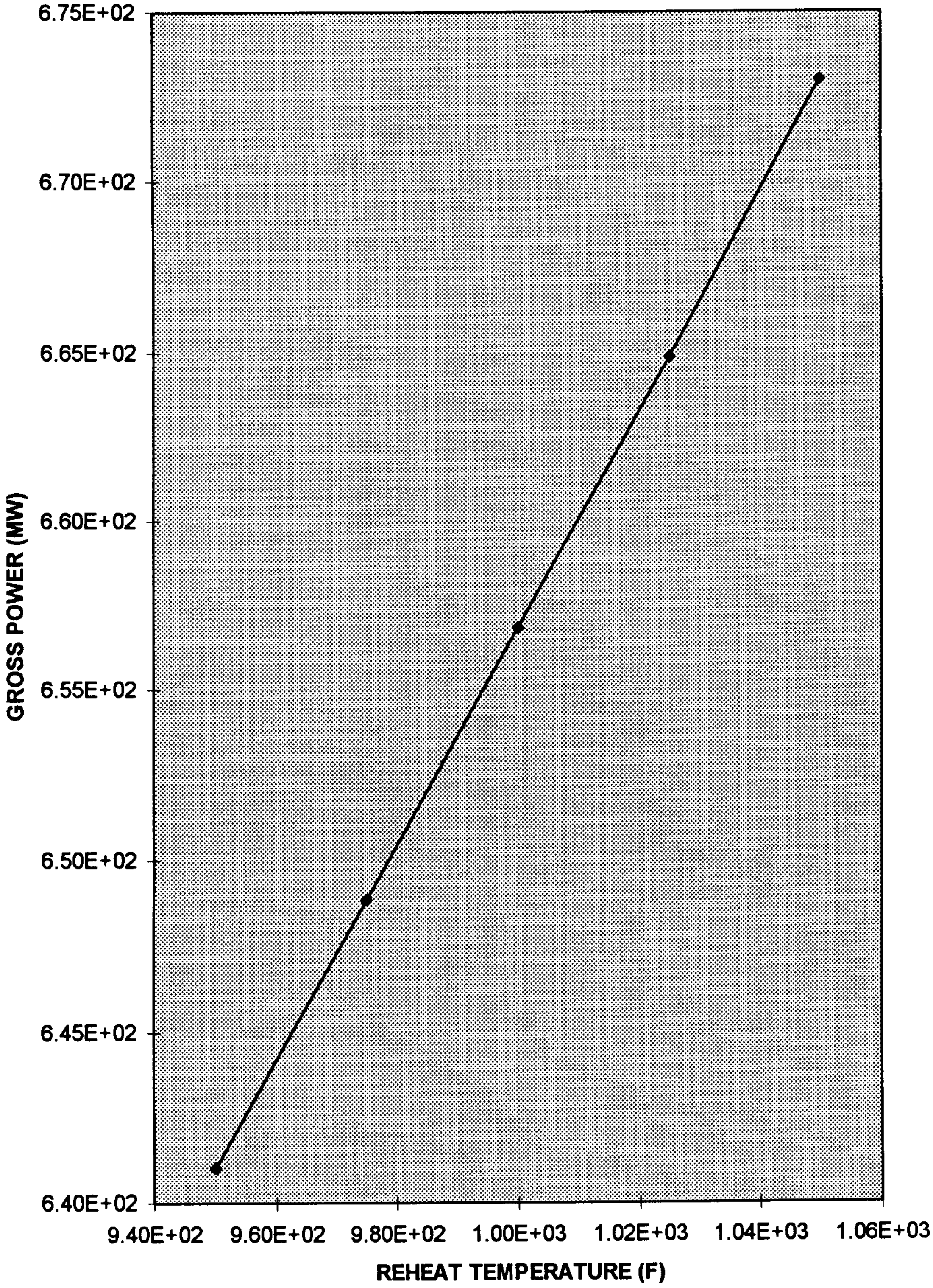

Figure 8 Gross Heat Rate as a Function of Reheat Pressure Drop

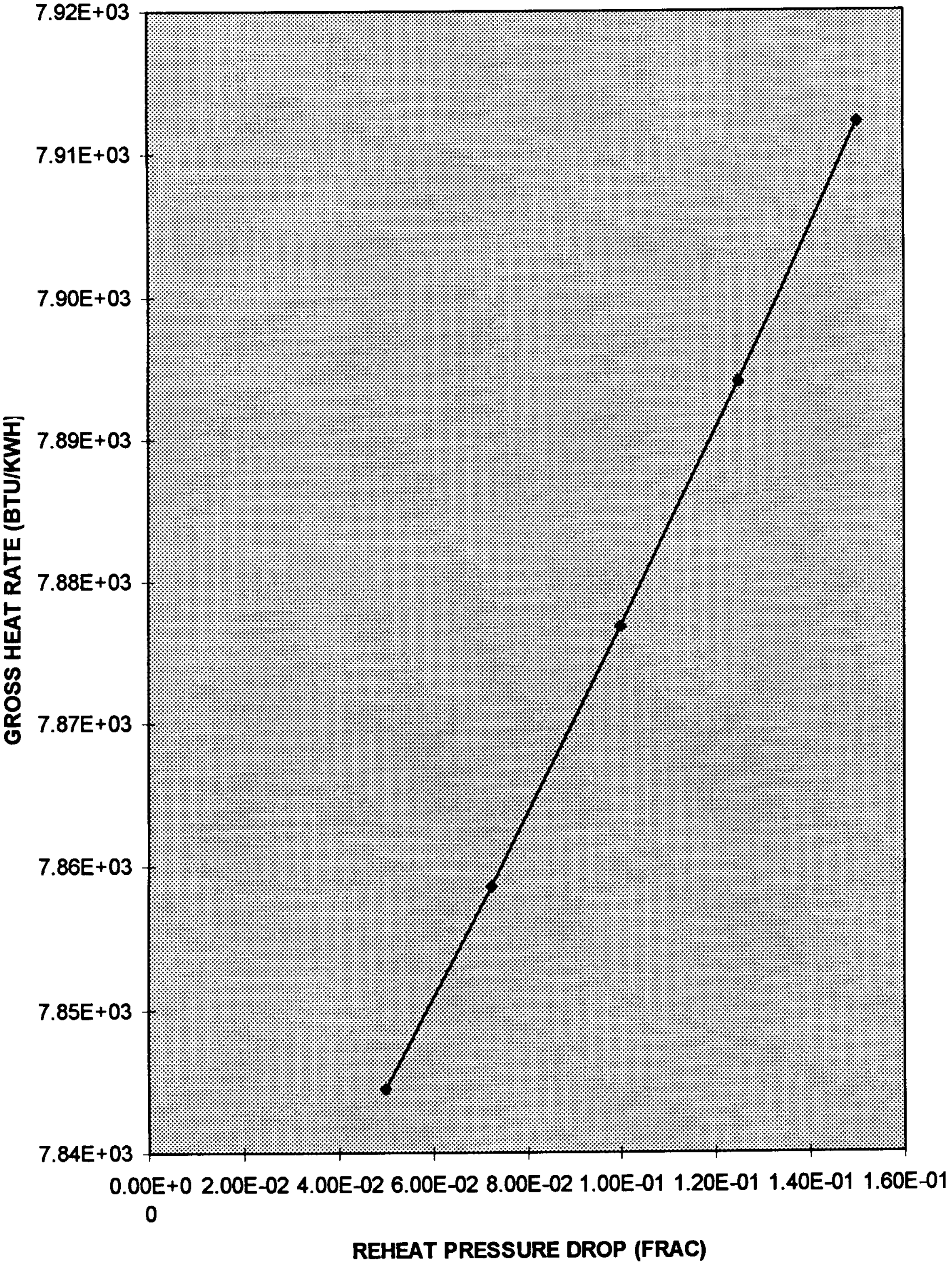

Figure 9 Gross Power as a Function of Reheat Pressure Drop

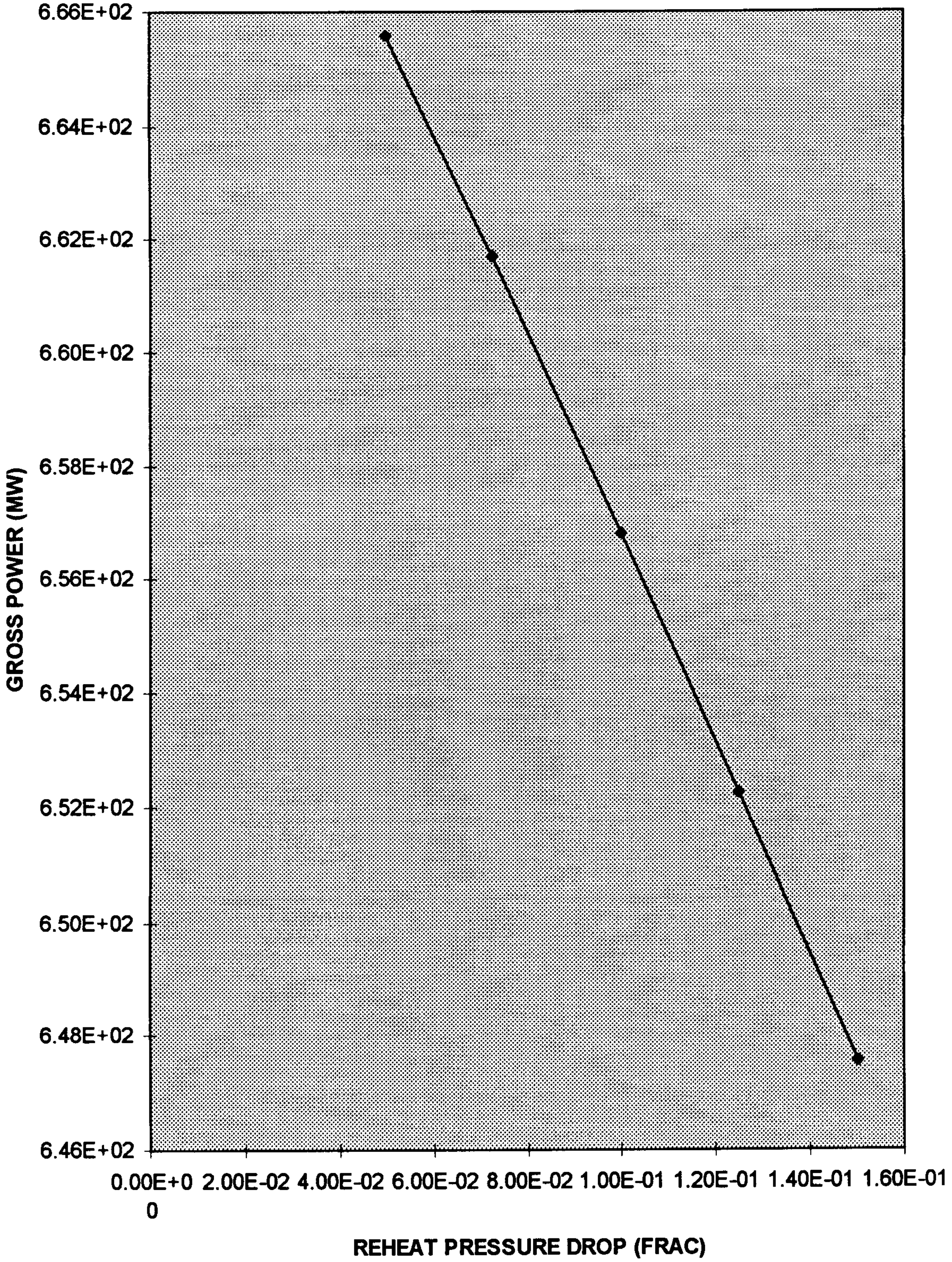

Figure 10 Gross Heat Rate as a Fucntion of Condenser Pressure

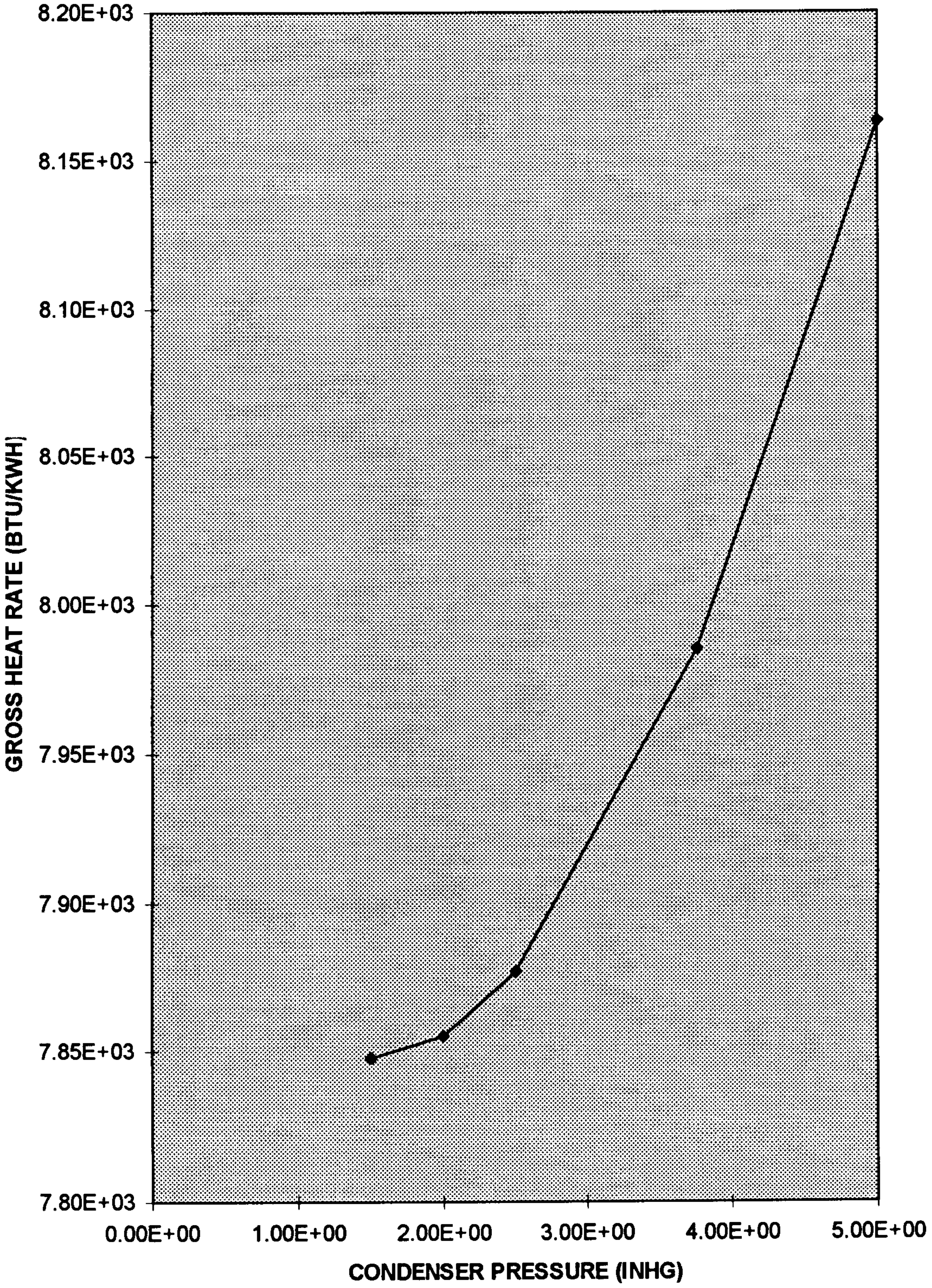

Figure 11 Gross Power as a Function of Condenser Pressure

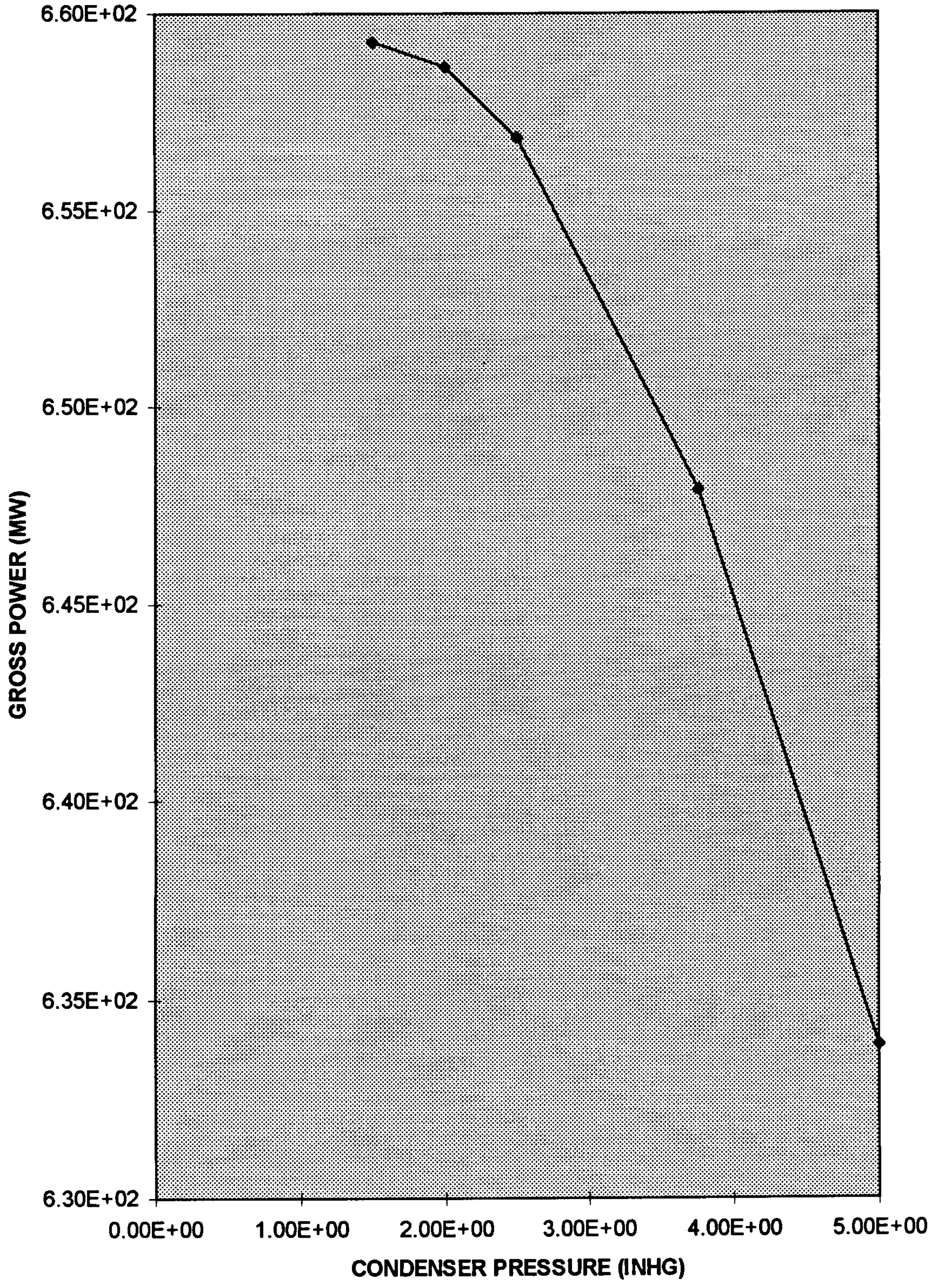

Table 1 Performance Sensitivities to Main Steam Temperature Offsets at VWO

MAIN STEAM MODEL TEMP	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5
MAIN STEAM TEMP (DEG F)[1]	1050	1025	1000	975	950
THROTTLE FLOW RATE	4.38E+06	4.44E+06	4.50E+06	4.56E+06	4.63E+06

RESULT[2]	CASE 1[3,4]	CASE 2	CASE 3	CASE 4	CASE 5
POWER	6.54E+02	6.55E+02	6.57E+02	6.59E+02	6.61E+02
HEAT RATE	7.81E+03	7.84E+03	7.88E+03	7.91E+03	7.95E+03
DELTA POWER	-2.84E+00	-1.52E+00	0.00E+00	1.74E+00	3.72E+00
DELTA HEAT RATE	-6.67E+01	-3.38E+01	0.00E+00	3.47E+01	7.07E+01

DEVIATION FROM DESIGN %

	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5
	-0.432965944	-0.231151655	0	0.26514768	0.566970875
	-0.846197324	-0.428856099	0	0.440916884	0.897639743

(1) Other boundary conditions at design values
(2) Delta PP = PP(casen) - PP(case 3) where PP is Performance Parameter
(3) Vendor Correction is -2.7
(4) Vendor Correction is -60.7

Table 2 Performance Sensitivities to Main Steam Pressure Offsets at VWO

MAIN STEAM MODEL PRES	CASE 11	CASE 12	CASE 3 (DESIGN)	CASE 14	CASE 15
MAIN STEAM PRES (PSIA)[1]	2535.4	2475.1	2414.7	2354.3	2294
THROTTLE FLOW RATE	4.38E+06	4.26E+06	4.50E+06	4.74E+06	4.62E+06

RESULT[2]	CASE 11[3,4]	CASE 12	CASE 3	CASE 14	CASE 15
POWER	6.89E+02	6.73E+02	6.57E+02	6.41E+02	6.24E+02
HEAT RATE	7.86E+03	7.87E+03	7.88E+03	7.89E+03	7.90E+03
DELTA POWER (3)	3.23E+01	1.62E+01	0.00E+00	-1.62E+01	-3.25E+01
DELTA HEAT RATE (4)	-1.77E+01	-9.22E+00	0.00E+00	9.77E+00	2.01E+01

DEVIATION FROM DESIGN %

	CASE 11	CASE 12	CASE 3	CASE 14	CASE 15
	4.913757733	2.464308361	0	-2.47141814	-4.94653581
	-0.224254415	-0.117014999	0	0.124010254	0.255777497

(1) Other boundary conditions at design values
(2) Delta PP = PP(casen) - PP(case 3) where PP is Performance Parameter
(3) Vendor Correction is 32.2
(4) Vendor Correction is -23.6

Table 3 Performance Sensitivities to Reheat Temperature Offsets at VWO

REHEAT MODEL TEMP	CASE 21	CASE 22	CASE 3	CASE 24	CASE 25
REHEAT TEMP (DEG F)[1]	1050	1025	1000	975	950
RESULT[2]	CASE 21[3,4]	CASE 22	CASE 3	CASE 24	CASE 25
POWER	6.73E+02	6.65E+02	6.57E+02	6.49E+02	6.41E+02
DELTA POWER (3)	7.82E+03	7.85E+03	7.88E+03	7.90E+03	7.93E+03
DELTA HEAT RATE (4)	1.62E+01	8.05E+00	0.00E+00	-7.95E+00	-1.58E+01
DELTA HEAT RATE	-5.50E+01	-2.75E+01	0.00E+00	2.74E+01	5.47E+01
DEVIATION FROM DESIGN %					
	CASE 21	CASE 22	CASE 3	CASE 24	CASE 25
	2.463288328	1.225074847	0	-1.210124513	-2.406059909
	-0.697862372	-0.349191445	0	0.347667978	0.69420605

(1) Other boundary conditions at design values
(2) Delta PP = PP(casen) - PP(case 3) where PP is Performance Parameter
(3) Vendor Correction is -15.4
(4) Vendor Correction is -55.1

Table 4 Performance Sensitivities to Reheat Pressure Drop Offsets at VWO

REHEAT MODEL PRES	CASE 31	CASE 32	CASE 3	CASE 34	CASE 35
REHEAT PRES DROP (FRAC)[1]	0.15	0.125	0.1	0.0725	0.05
RESULT[2]	CASE 31[3,4]	CASE 32	CASE 3	CASE 34	CASE 35
POWER	6.48E+02	6.52E+02	6.57E+02	6.62E+02	6.66E+02
HEAT RATE	7.91E+03	7.89E+03	7.88E+03	7.86E+03	7.84E+03
DELTA POWER (3)	-9.31E+00	-4.58E+00	0.00E+00	4.88E+00	8.75E+00
DELTA HEAT RATE (4)	3.54E+01	1.73E+01	0.00E+00	-1.82E+01	-3.23E+01
DEVIATION FROM DESIGN %					
	CASE 31	CASE 32	CASE 3	CASE 34	CASE 35
	-1.41755659	-0.697276284	0	0.742949403	1.331706355
	0.44929595	0.219214277	0	-0.230437154	-0.409825451

(1) Other boundary conditions at design values
(2) Delta PP = PP(casen) - PP(case 3) where PP is Performance Parameter
(3) Vendor Correction is -8.9
(4) Vendor Correction is 39.4

Table 5 Performance Sensitivities to Condenser Pressure Offsets at VWO

CONDENSER MODEL	**CASE 41**	**CASE 42**	**CASE 3**	**CASE 44**	**CASE 45**
CONDENSER PRES (INHG)[1]	5	3.75	2.5	2	1.5
RESULT[2]	**CASE 41**[3,4]	**CASE 42**	**CASE 3**	**CASE 44**	**CASE 45**
POWER	6.34E+02	6.48E+02	6.57E+02	6.59E+02	6.59E+02
HEAT RATE	8.16E+03	7.99E+03	7.88E+03	7.86E+03	7.85E+03
DELTA POWER (3)	-2.30E+01	-8.94E+00	0.00E+00	1.79E+00	2.42E+00
DELTA HEAT RATE (4)	2.86E+02	1.09E+02	0.00E+00	-2.14E+01	-2.89E+01
DEVIATION FROM DESIGN %					
	CASE 41	**CASE 42**	**CASE 3**	**CASE 44**	**CASE 45**
	-3.50331092	-1.36041952	0	0.272166116	0.368658192
	3.630486514	1.379195122	0	-0.271431125	-0.367308013

(1) Other boundary conditions at design values

(2) Delta PP = PP(casen) - PP(case 3) where PP is Performance Parameter

(3) Vendor Correction is -26.3

(4) Vendor Correction is 315.1

Table 6A Performance Sensitivities to Combined Boundary Condition Offsets, Each Case Calculated by a Single PEPSE RUN

COMBINED ANALYSIS	CASE 101	CASE 102	CASE 3	CASE 104	CASE 105
MAIN STEAM TEMP (DEG F)	1050	1025	1000	975	950
MAIN STEAM PRES (PSIA)	2535.4	2475.1	2414.7	2354.3	2294
REHEAT TEMP (DEG F)	1050	1025	1000	975	950
REHEAT PRES DROP (FRAC)	0.15	0.125	0.1	0.0725	0.05
CONDENSER PRES (INHG)	5	3.75	2.5	2.0	1.5
THROTTLE FLOW (LB/HR)	6.71E+02	6.66E+02	4.50E+06	4.44E+06	4.44E+06
RESULT OF COMBINED	**CASE 101[1,2]**	**CASE 102**	**CASE 3**	**CASE 104**	**CASE 105**
POWER	6.71E+02	6.66E+02	6.57E+02	6.41E+02	6.17E+02
HEAT RATE	8.03E+03	7.93E+03	7.88E+03	7.91E+03	8.03E+03
DELTA POWER	1.38E+01	9.33E+00	0.00E+00	-1.58E+01	-3.95E+01
DELTA HEAT RATE	1.54E+02	4.93E+01	0.00E+00	3.06E+01	1.49E+02

(1) Vendor Corrections (Superposed) gives 666.6 MW

(2) Vendor Corrections (superposed) gives 8092 BTU/KWH

Table 6B Performance Sensitivities to Combined Boundary Condition Offsets, Results Shown Are Calculated by Algebraic Superposition of Deviations from PEPSE Runs of Single Effects, as presented in Tables 1-5

ALGEBRAIC SUPERPOSITION OF INDIVIDUAL CASES (POWER AND HEAT RATE)					
MAIN STEAM TEMP	-2.84E+00	-1.52E+00	0.00E+00	1.74E+00	3.72E+00
CASES 1,2,3,4 & 5	-6.67E+01	-3.38E+01	0.00E+00	3.47E+01	7.07E+01
MAIN STEAM PRES	3.23E+01	1.62E+01	0.00E+00	-1.62E+01	-3.25E+01
CASES 11,12,3,14 & 15	-1.77E+01	-9.22E+00	0.00E+00	9.77E+00	2.01E+01
REHEAT TEMP	1.62E+01	8.05E+00	0.00E+00	-7.95E+00	-1.58E+01
CASE2 21,22,3,24 & 25	-5.50E+01	-2.75E+01	0.00E+00	2.74E+01	5.47E+01
REHEAT PRES DROP	-9.31E+00	-4.58E+00	0.00E+00	4.88E+00	8.75E+00
CASES 31,32,3,34 & 35	3.54E+01	1.73E+01	0.00E+00	-1.82E+01	-3.23E+01
CONDENSER PRES	-2.30E+01	-8.94E+00	0.00E+00	1.79E+00	2.42E+00
CASES 41,42,3,44 & 45	2.86E+02	1.09E+02	0.00E+00	-2.14E+01	-2.89E+01
TOTAL DELTA POWER	1.33E+01	9.20E+00	0.00E+00	-1.58E+01	-3.34E+01
TOTAL DELTA HEAT RATE	1.82E+02	5.54E+01	0.00E+00	3.24E+01	8.43E+01

Table 7A Performance Parameter Deviations From Design Values for Combined Offset Cases of Table 6A

DEVIATION FROM DESIGN % FOR ANALYZED COMBINED ((DELTA/DESIGN)*100)					
	CASE 101	CASE 102	CASE 3	CASE 104	CASE 105
POWER	2.093366512	1.420890732	0	-2.403091157	-6.020417407
HEAT RATE	1.957541469	0.625675404	0	0.388890469	1.895295126

Table 7B Performance Parameter Deviations From Design Values for (Superposed) Combined Offset Case of Table 6B

DEVIATION FROM DESIGN % FOR SUPERPOSED RESULTS ((DELTA/DESIGN)*100)					
POWER	2.023212602	1.400535746	0	-2.401279456	-5.085260295
HEAT RATE	2.311468359	0.703346855	0	0.410726836	1.070489825

Table 7C Net Deviation Between PEPSE Results and Algebraic Superposition

(DELTA SUPERPOSED - DELTA COMBINED)					
DELTA POWER	-4.61E-01	-1.34E-01	0.00E+00	1.19E-02	6.14E+00
DELTA HEAT RATE	2.79E+01	6.12E+00	0.00E+00	1.72E+00	-6.50E+01

The main purpose of this analysis is to determine the accuracy of superposing these effects. Therefore, corrections from the vendor's individual curves were superposed for the full range combination of offsets of boundary conditions and compared to the PEPSE results. The result of the comparison is provided in Table 6A as a footnote. As shown, there is a significant difference between the superposed vendor results and the combined PEPSE run results.

Conclusions

Vendor's correction curves provide reasonably accurate predictions of deviations of performance parameters when treated as the effect of variation of a single boundary condition. Even for such cases, it is well to remember that the correction curves apply to a "generic' system of similar size. For best accuracy, PEPSE should be used to run a heat balance analysis of the system as it is actually configured and currently operating. For best results, PEPSE should be utilized to verify or correct the generic vendor supplied deviation curves.

The benefit of verifying the vendor curves is demonstrated by Reference 4, for example. This type of analysis has been performed and used many times over the years.

The PEPSE code is specifically designed to combine the effects of varying several boundary conditions at one time. The PEPSE code saves valuable man hours analyzing a system eliminating the need to read and apply each of the correction curves. In addition, the PEPSE code reduces the possibility of human error in reading and interpreting the curves.

It can also be observed from these analyses that the correction curves for generation were in closer agreement with the heat balance results than were the curves for heat rate.

When several steam turbine cycle boundary condition values are offset from their standard values, it is still possible to superpose the single-effect correction curves in order to determine the combined correction for all of the offsets. In this study, this superposition worked well when the offsets were reasonably "small". We define small as offsets at the mid-range for offsets of the conditions. Especially for offsets of boundary conditions to high values, superposition still provided good predictions. On the other hand, the predictions were not so good at the opposite end of the offset range. Of course, the heat balance analysis provides an easy to use, quick, repeatable, and reliable prediction of all of the effects of combining all of the offsets, no matter how far they deviate from the standard conditions. Economically, the PEPSE code justifies its use by saving valuable man hours, in addition to providing improved confidence in the heat rates obtained by analyzing and identifying problem areas.

References

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