Development of Controllable Parameter Heat Rate Effect Curves Using PEPSE®

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ABSTRACT

On-line controllable loss monitoring systems require a method to calculate the heat rate impact of off design operation. Most systems utilize the correction curves supplied by the turbine vendor for the four primary losses (initial pressure, initial temperature, reheat temperature, and exhaust pressure). Using the generic curves provided by the turbine manufacturer may not provide the desired accuracy in your performance monitoring system results.

This paper outlines a method to develop heat rate effect curves for the primary controllable parameters using the PEPSE heat balance code. The results of this method will be compared to the curves supplied by General Electric for one of the 270 megawatt steam turbines owned and operated by Santee Cooper.

INTRODUCTION

In 1985, Santee Cooper developed a goals program in an attempt to monitor and improve system operations, safety, and budget control. The three primary goals focused on heat rate, system availability, and safety. This program has resulted in a net system heat rate of 9954 Btu/kW-hr in 1989 compared to 10,163 Btu/kW-hr in 1985. Availability has increased from 82 percent in 1985 to almost 91 percent in 1989. The number of recordable accidents dropped from 60 to 29 in the same time period.

Continuation of the heat rate and availability trends will require constant monitoring of plant performance and improved tools to provide plant personnel with essential information. To that end, Santee Cooper has been evaluating various on-line performance monitoring systems for the past several years. After reviewing several commercially available systems, a decision was made to develop a controllable loss monitoring system in-house. The in-house option was determined to be the most cost effective method, based on the limited capabilities the system was expected to include. The system's primary functions are monitoring the operator controllable parameters (main steam pressure, main steam temperature, hot reheat temperature, condenser pressure, superheat spray, and dry gas losses) and calculating the change in operating costs when a parameter deviates from design.

To maintain consistency with Santee Cooper's performance testing program, the controllable loss monitoring system results need to match those presented in regular performance test reports. Therefore, all of the on-line system calculations have to be based on plant specific PEPSE analyses. This paper outlines the methods used to develop the controllable loss calculations and compares the PEPSE generated curves with the turbine manufacturer's heat rate effect curves for throttle pressure, throttle temperature, hot reheat temperature, and condenser pressure.

All analysis and comparisons referred to in this report are based upon the prototype system being installed at Santee Cooper's Winyah Generating Station, Unit 1. Winyah 1 is a 270 megawatt General Electric turbine/generator utilizing a Riley Stoker boiler. The analyses are based entirely upon turbine cycle response. Changes in boiler efficiency resulting from varying boundary conditions are not considered in these studies.

PEPSE ANALYSIS

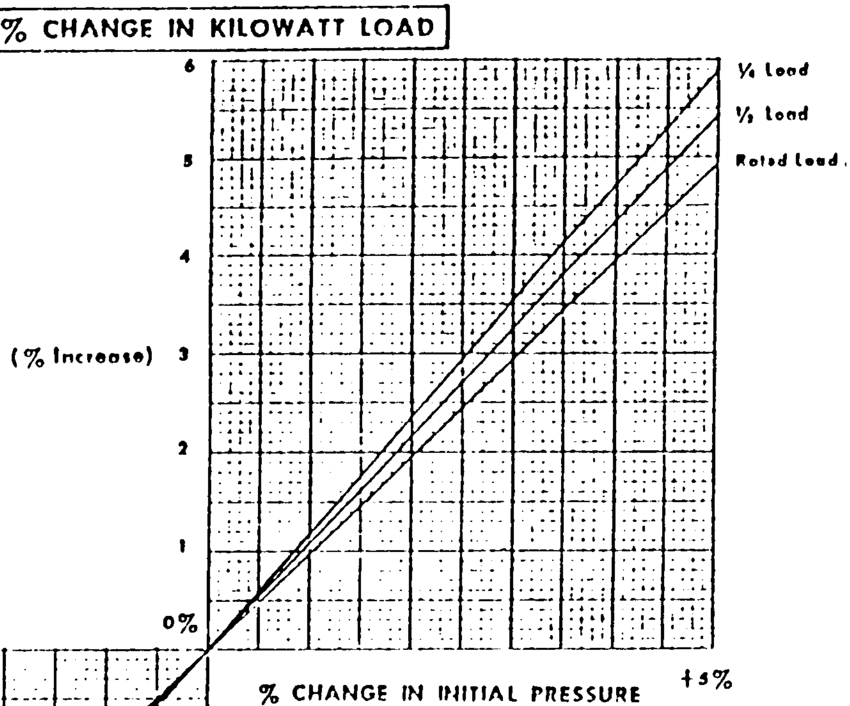
The equations used in Santee Cooper's on-line controllable loss monitoring system (referred to as OLS) are based on a series of sensitivity studies performed on plant specific models using PEPSE. These sensitivity studies were performed on a design turbine cycle model utilizing General Electric turbine solution procedures (PEPSE turbine types 04 - 07) with all other components (condenser, feedwater heaters, etc.) in performance mode. Several PEPSE runs were then made while varying one controllable parameter through a specified range and holding all other boundary conditions constant.

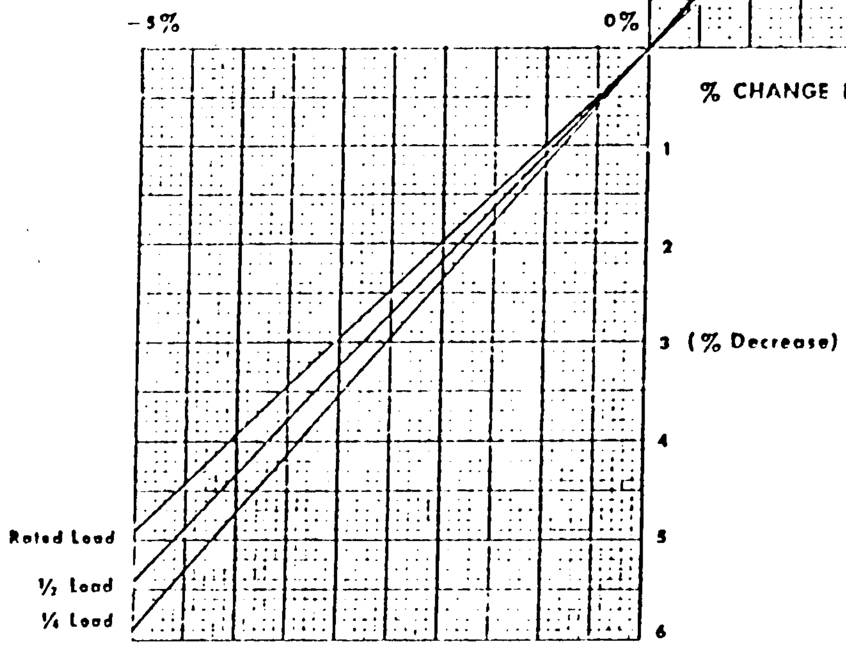
The ranges used for the sensitivity analyses were selected to ensure that the boundaries would not be exceeded during regular operation. The unit was analyzed at 25 percent, 50 percent, 75 percent, 100 percent, and valves-wide-open (VWO) load points. Throttle pressure, throttle temperature, and hot reheat temperature were varied from 90 percent to 110 percent of their design values at each load point. Condenser pressure was varied from 0.75 inches Hga to 5.0 inches Hga at each load point. Superheat sprays were varied from no flow to approximately 10 percent of the feedwater flow at each load point.

The correction curves supplied by General Electric (Figures 1 - 4) assume a constant control valve opening, and the corrections are supposed to be applied to heat rates at rated steam conditions (design heat rate). Therefore, the sensitivity studies for throttle pressure and throttle temperature should include PEPSE's Special Option 1 to

INITIAL PRESSURE CORRECTION FACTORS

FOR SINGLE REHEAT UNITS





METHOD OF USING CURVES

These correction factors assume constant control valve opening and are to be applied to heat rates and kilowatt loads at rated steam conditions.

1. The heat rate at the desired condition can be found by multiplying the heat rate at rated conditions by the following:

$$1 + \frac{\text{\% change in gross heat rate}}{100}$$

2. The kilowatt load at the desired conditions can be found by multiplying the kilowatt load at rated conditions by the following:

$$1 + \frac{\text{\% change in kw load}}{100}$$

3. These correction factors are not guaranteed.

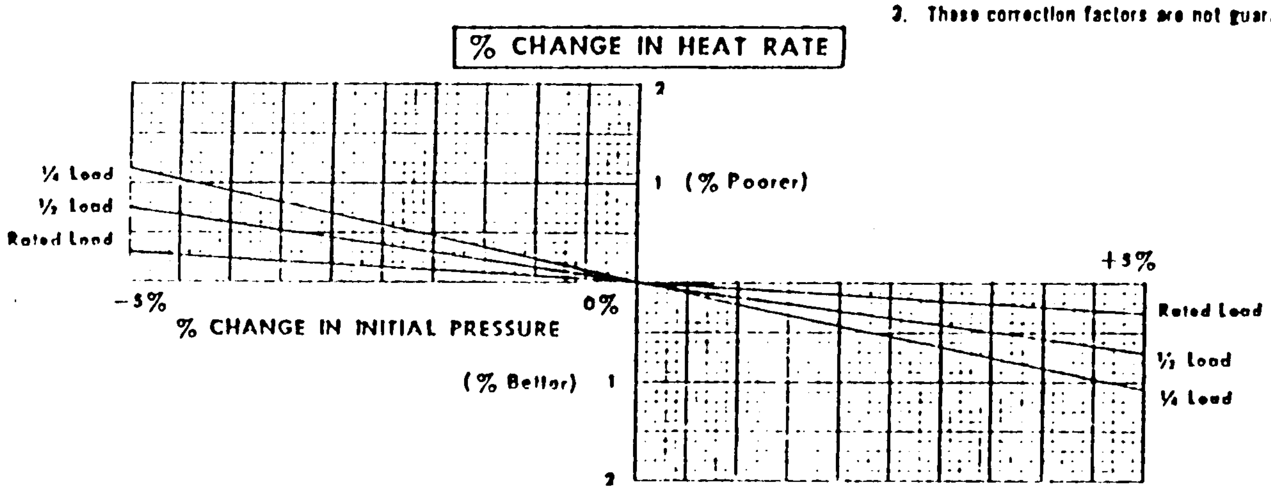
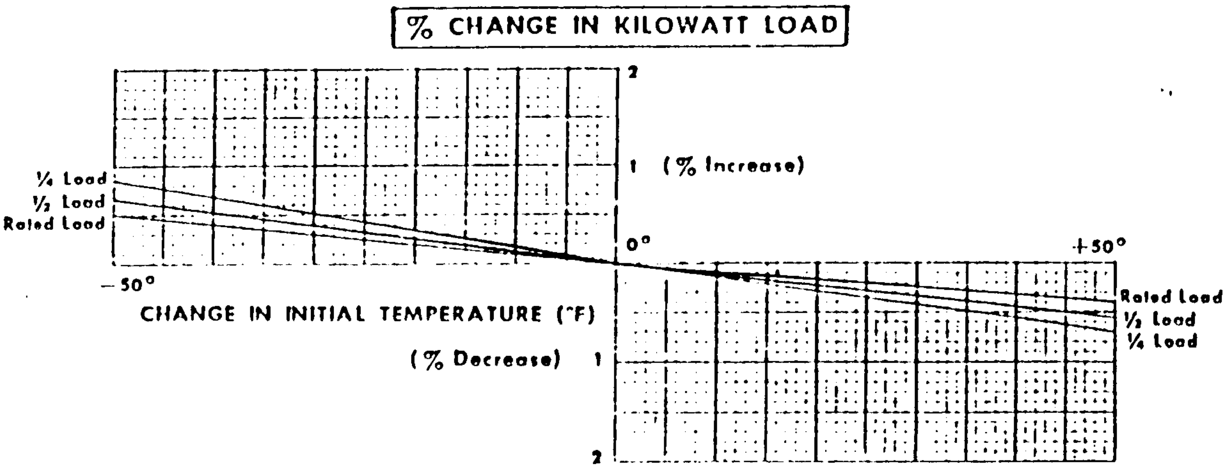


Figure 1

INITIAL TEMPERATURE CORRECTION FACTORS

FOR SINGLE REHEAT – SUBCRITICAL PRESSURE UNITS



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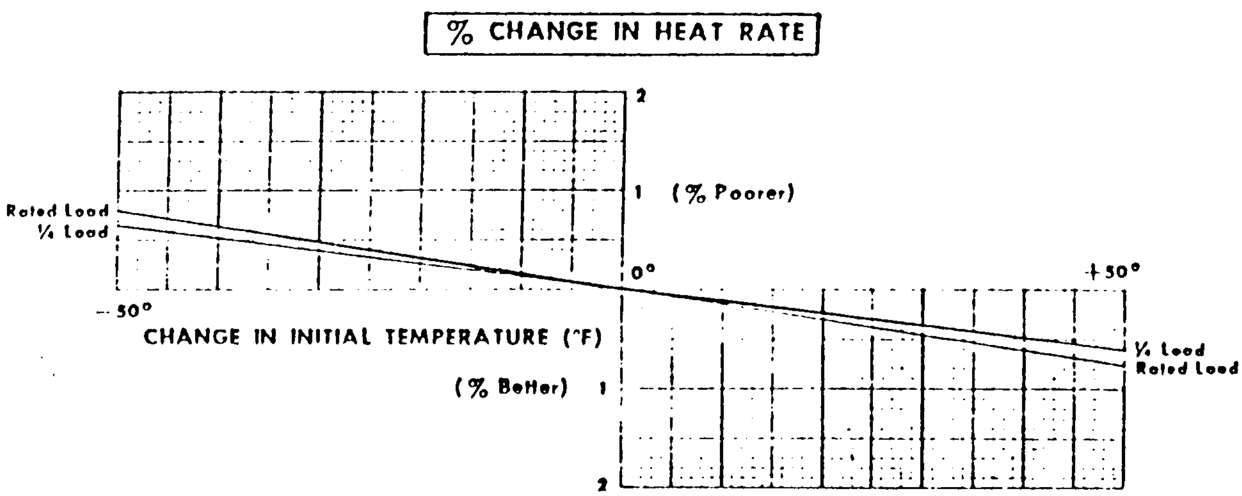
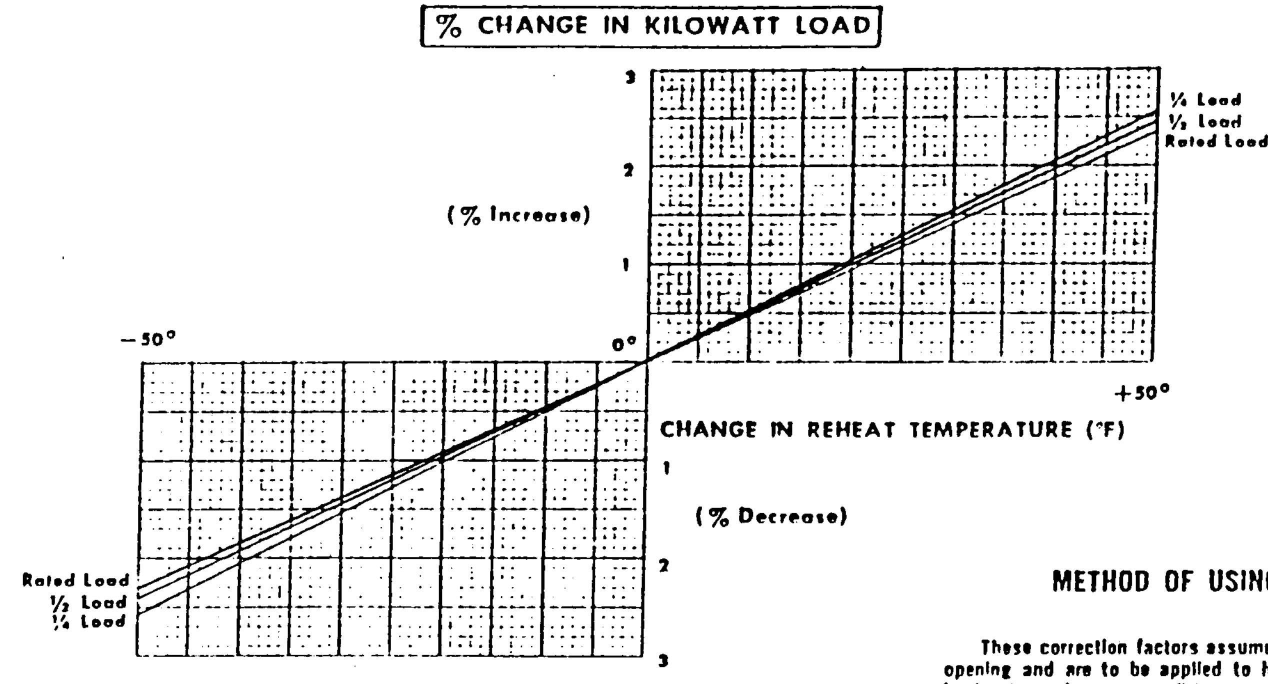


Figure 2

GEZ-3615
6-67 (2M)

GENERAL ELECTRIC

REHEAT TEMPERATURE CORRECTION FACTORS
FOR SINGLE REHEAT UNITS



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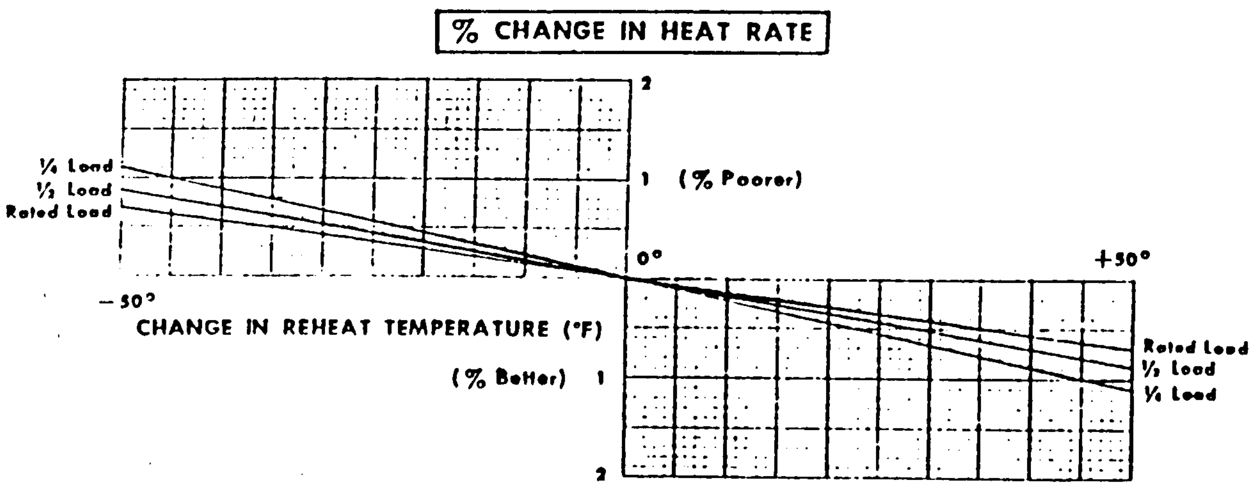


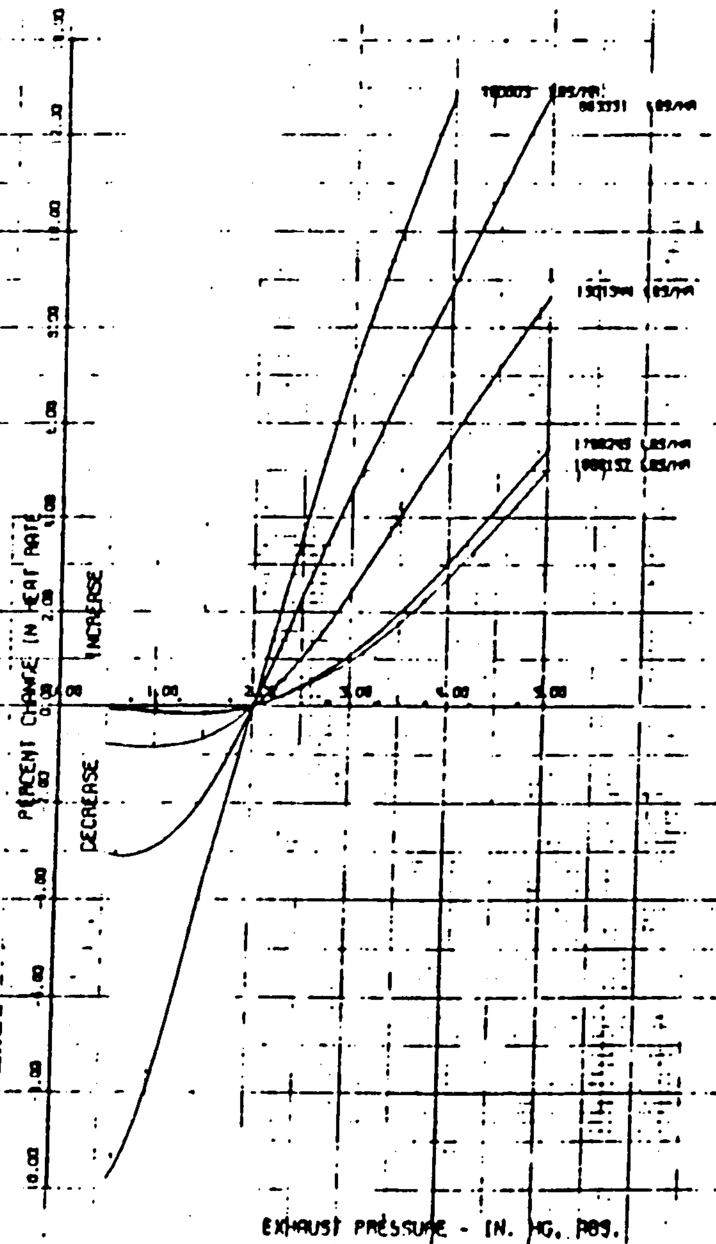
Figure 3

GEZ-3617
6-75 (2500)

GENERAL ELECTRIC

EXHAUST PRESSURE CORRECTION FACTORS

270,719 KW AT 3.5 IN. HG. ABS, 1 PCT MU
TC2F 30 IN. LSB, 3600 RPM.
2400 PSIG 1000/1000 F



METHOD OF USING CURVE

FLOWS NEAR CURVES ARE THROTTLE FLOWS AT 2400 PSIG 1000 F
THESE CORRECTION FACTORS ASSUME CONSTANT CONTROL VALVE OPENING
APPLY CORRECTIONS TO HEAT RATES AND KW LOADS
AT 2.0 IN. HG. ABS. AND 0 PCT MU

THE PERCENT CHANGE IN KW LOAD FOR VARIOUS EXHAUST PRESSURES IS EQUAL TO
(MINUS PCT CHANGE IN HEAT RATE)100/(100 + PCT CHANGE IN HEAT RATE).

THESE CORRECTION FACTORS ARE NOT GUARANTEED

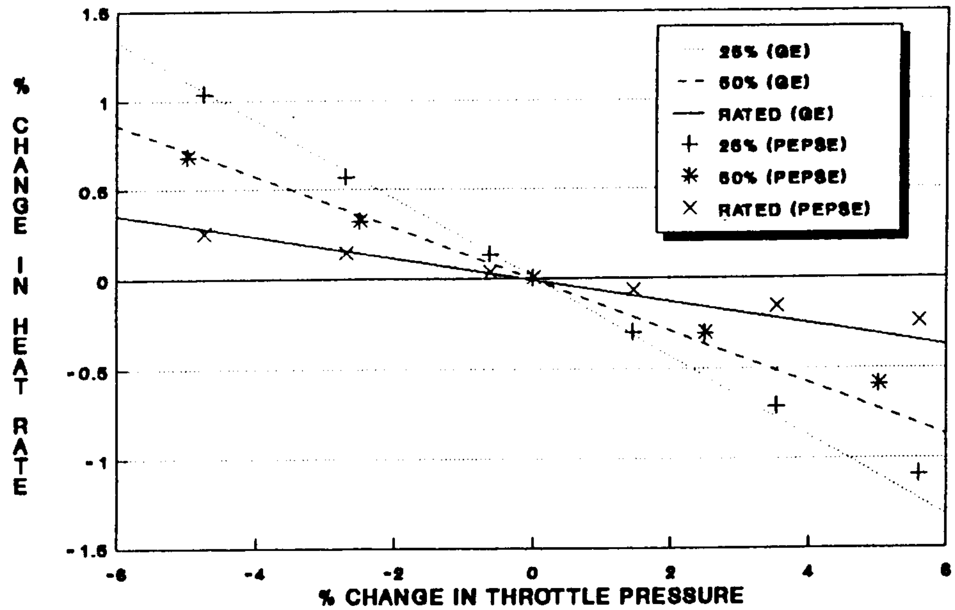
GENERAL ELECTRIC COMPANY, SCHENECTADY, NEW YORK 07/15/71

Figure 4

simulate a constant throttle valve position. Sensitivity studies performed for any other controllable parameter will provide the same results whether Special Option 1 or a constant throttle flow is specified. Variations in these other parameters do not effect throttle valve conditions and, therefore, have no effect on the mass flow rate.

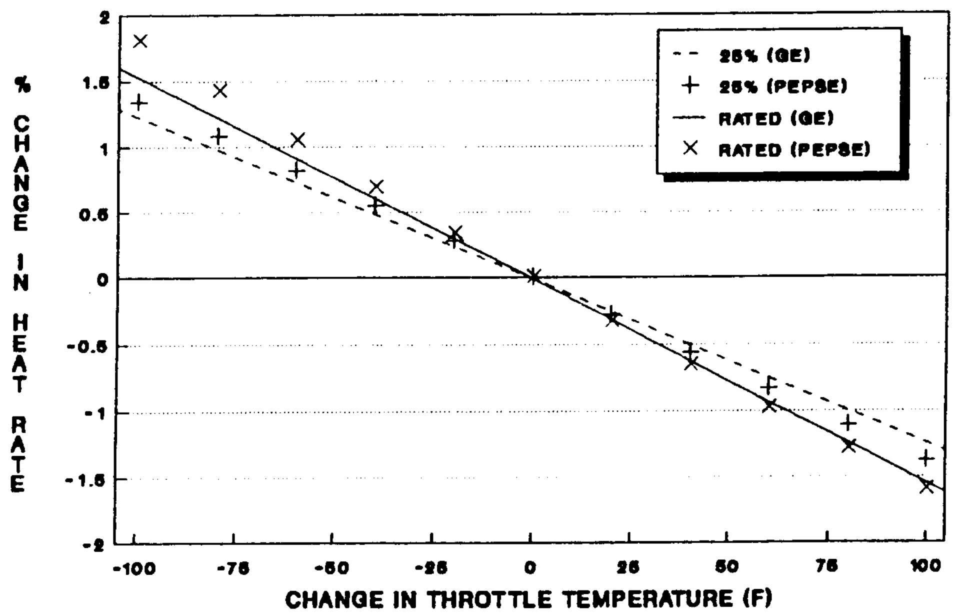
Figures 5 through 8 present a comparison between the General Electric correction curves supplied for Winyah 1 and the results of the PEPSE analyses. The PEPSE generated points reproduce the GE curves very well for reheat temperature and condenser pressure. The results for throttle pressure and throttle temperature, however, do not reproduce the GE curves nearly as well. Since the GE correction curves are the same for all single reheat, subcritical pressure units and the PEPSE analysis was performed on a plant specific model, the PEPSE results should provide a more accurate prediction of the true unit response.

Turbine design does not consider the use or effect of sprays, therefore, the results of the spray flow sensitivity studies can not be compared with any GE supplied data. The change in gross turbine heat rate caused by increasing superheat spray flow from zero to ten percent of feedwater flow was only 0.3 percent at full load. This indicates that superheat sprays have a very small effect on turbine heat rate. The OLS does monitor sprays and calculate a change in heat rate for off-target spray operation, however, superheat spray analysis will not be discussed any further in this paper.



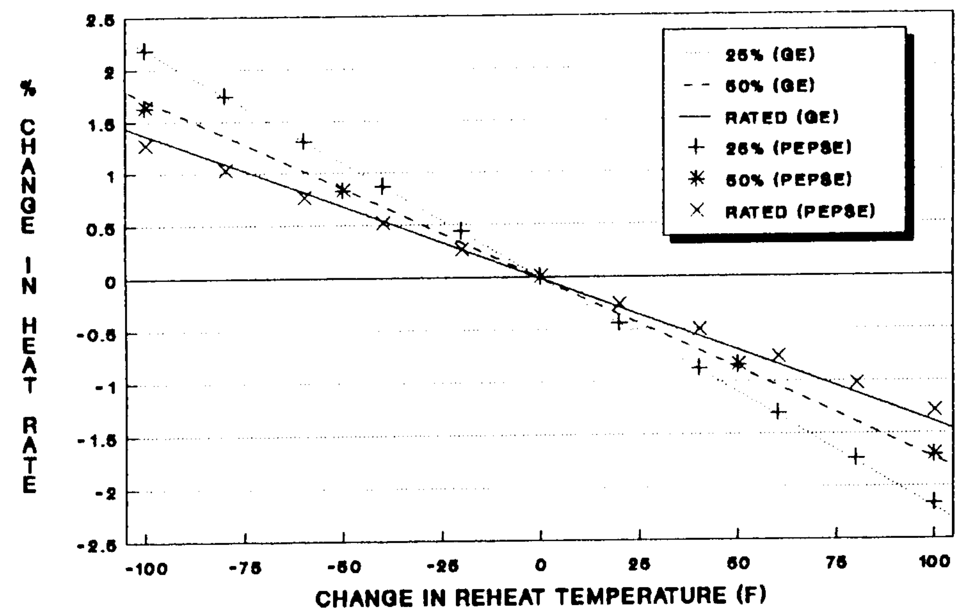
Throttle Pressure Correction Factors

Figure 5



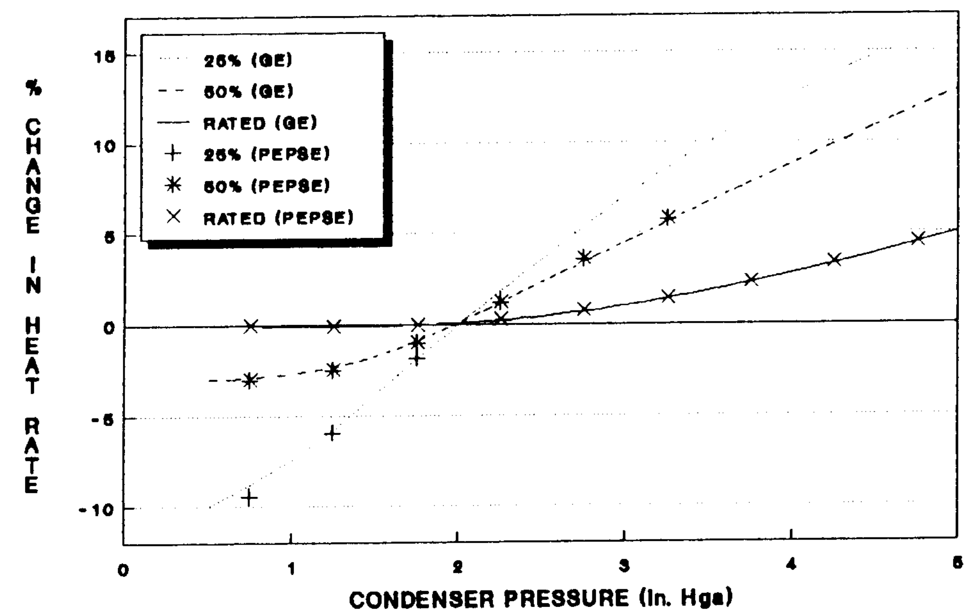
Throttle Temperature Correction Factors

Figure 6



Reheat Temperature Correction Factors

Figure 7



Exhaust Pressure Correction Factors

Figure 8

SOFTWARE DEVELOPMENT

Incorporating the controllable parameter heat rate correction curves into a controllable loss monitoring system involves three primary steps. First, the measured steam flow must be corrected for off-design throttle conditions. Second, the correction curves must be put into a format that can be quickly solved by the computer system. Third, the design heat rate for the operating load must be calculated.

The first step, calculating the design flow for the operating load, was performed using the simplified Martin's formula:

$$m = C\sqrt{p/v}$$

where:
- m = throttle mass flow
- C = throttle valve flow coefficient
- p = throttle pressure
- v = throttle specific volume

The throttle valve flow coefficient (C) can be calculated using the measured steam flow (m) and throttle pressure (p) and a specific volume (v) based on the measured throttle pressure and temperature. This flow coefficient (C) can then be used in the same equation with the design throttle pressure (p) and specific volume (v) to calculate a design throttle flow (m) for the operating throttle valve position.

The second step, programming the correction curves, was accomplished by applying a least squares curve fit analysis to the PEPSE results. Using the controllable parameter value as the independent variable and the fractional change in heat rate as the dependent variable, a polynomial equation was developed for each load point. If the design flow falls between two load points, the equations for the adjacent load points can be solved and an interpolation performed to achieve the final result.

The third step, calculating a design heat rate, was also accomplished using least squares curve fit analysis. An equation was developed that calculates design heat rate based on flow. When this equation is used in the system software, the measured flow must be corrected for off-design throttle conditions. If measured flow were used directly, the change in mass flow caused by variations in throttle pressure and temperature would provide an erroneous design heat rate value.

In summary, implementing the PEPSE sensitivity study results into the OLS software required that the steam flow at design throttle conditions be calculated first. Polynomial equations were then used to calculate a fractional change in heat rate based on a measured controllable parameter value and a design heat rate based on design throttle flow. Finally, the fractional change in heat rate was multiplied by the design heat rate to produce the absolute change in heat rate caused by off-design operation of a controllable parameter.

BOILER MANUFACTURER'S OPERATING CURVES

All of the analysis presented thus far considers the turbine design conditions as operating targets for all controllable parameters. In the case of Winyah Unit 1, design throttle pressure is 2400 psig, design throttle and reheat temperatures are 1000° F, and design condenser pressure is 2.0 inches Hga at all load points. However, maintaining 1000° F throttle and reheat temperatures at low loads presents a problem.

Riley Stoker, the boiler manufacturer for Winyah 1, provided a set of operating curves that limit throttle and reheat temperatures based on primary steam flow (Figure 9). If achievable targets are to be provided for the unit operator, these curves must be considered in the development of the controllable loss equations. This can be easily accomplished by including the boiler design curves in the turbine cycle model through the use of PEPSE's Schedules. However, when using boiler design curves in turbine analysis, the heat lost between the boiler and throttle valve should be considered. For the Winyah 1 analysis, the throttle and reheat temperatures were reduced by five degrees from the boiler design data. After the boiler design curves

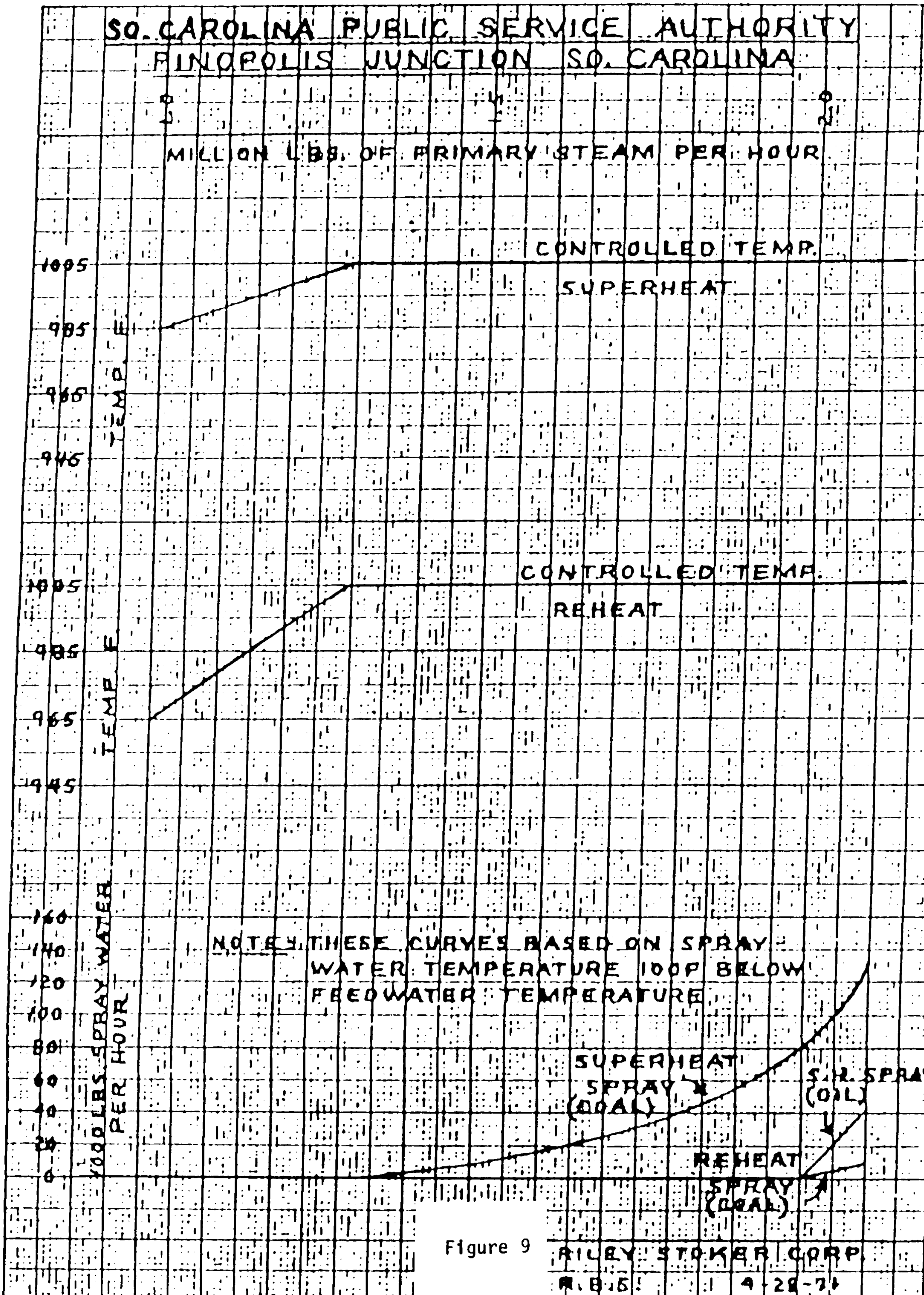

SO. CAROLINA PUBLIC SERVICE AUTHORITY
PINOPOLIS JUNCTION SO. CAROLINA
MILLION LBS. OF PRIMARY STEAM PER HOUR
CONTROLLED TEMP.
SUPERHEAT
1005
985
965
945
TEMP F
CONTROLLED TEMP.
REHEAT
NOTE: THESE CURVES BASED ON SPRAY WATER TEMPERATURE 100F BELOW FEEDWATER TEMPERATURE
1000 LBS SPRAY WATER PER HOUR
160
140
120
100
80
60
40
20
0
SUPERHEAT SPRAY (COAL)
S.H. SPRAY (OIL)
REHEAT SPRAY (COAL)
RILEY STOKER CORP.
4-29-71

Figure 9

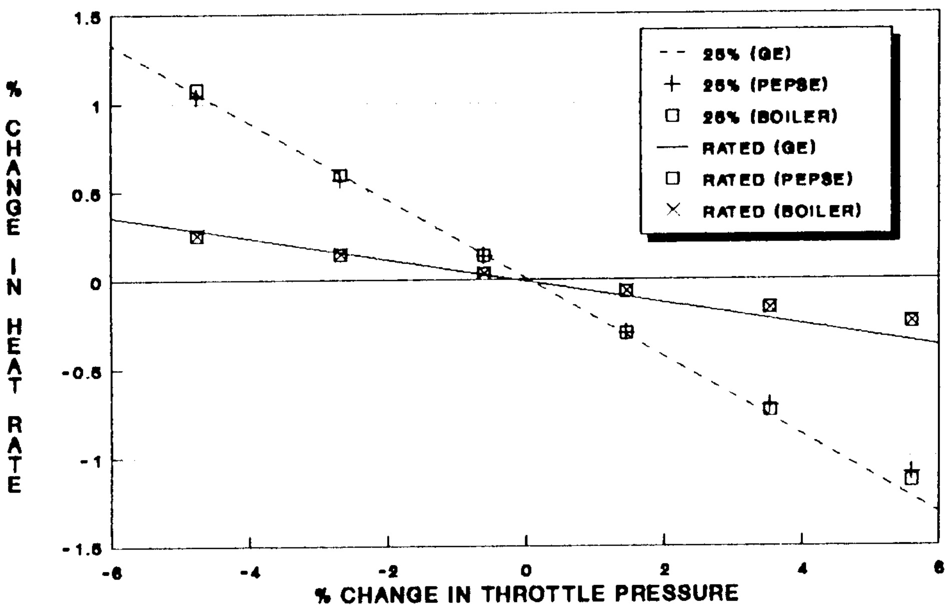
are corrected for heat loss and scheduled into the model, it can be run at several load points to develop a new target heat rate curve.

Special Option 1 should be used on all runs having throttle conditions that differ from turbine design. The turbine vendor supplies a design steam flow on the valve point heat balances, however, any change in throttle conditions will have an effect on the actual mass flow through the throttle valve. Turbine design throttle pressure, throttle enthalpy, and throttle flow should be used as reference conditions on the throttle valve input card (words 9, 10 and 11 on card 70YYYS, where YYY is the throttle valve component number) for all analysis that includes boiler design data. Special Option 1 will then adjust the throttle mass flow rate based on the turbine design throttle valve flow passing capability and the boiler design steam temperature.

The controllable parameter sensitivity studies are performed the same way they were before the boiler operating curves were included, with two exceptions. First, Special Option 1 must be used for all controllable parameter sensitivity studies. Second, the schedules for throttle temperature, reheat temperature, and superheat spray will have to be turned off for their respective sensitivity studies.

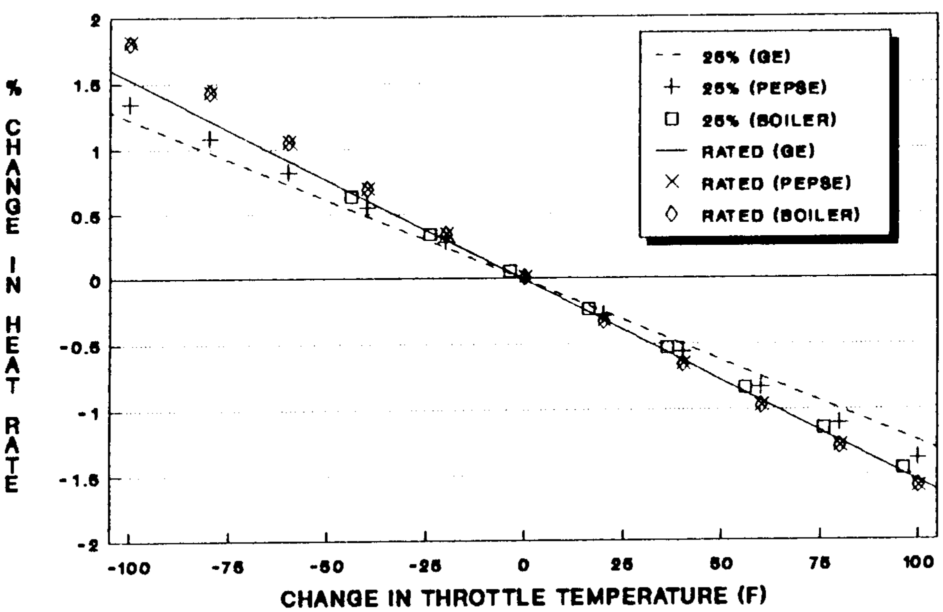
Figures 10 through 13 compare the GE correction curves with the curves generated by PEPSE using both the turbine design boundary conditions and the boiler design boundary conditions. These figures indicate boiler design operating data only affects OLS system results at low loads. Comparisons at rated load shows virtually no difference between the sensitivity studies run with boiler design conditions and those based entirely upon turbine design.

Implementing the results of these sensitivity studies into the OLS software presents another problem. The target throttle flow is different than the turbine design flow at the 25 and 50 percent load points. The lower throttle temperature defined by the boiler design curves results in a lower specific volume at the throttle valve which



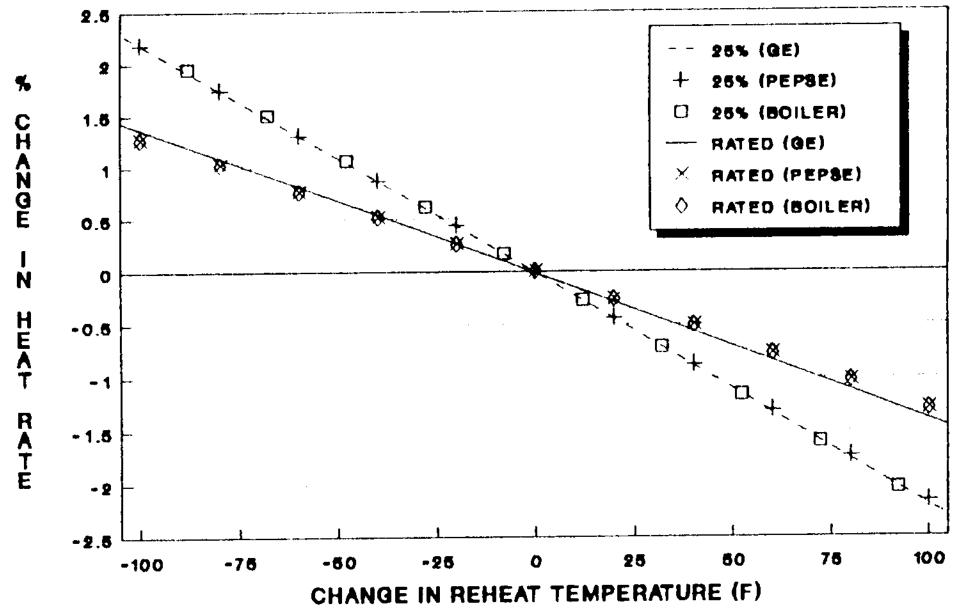
Throttle Pressure Correction Factors

Figure 10



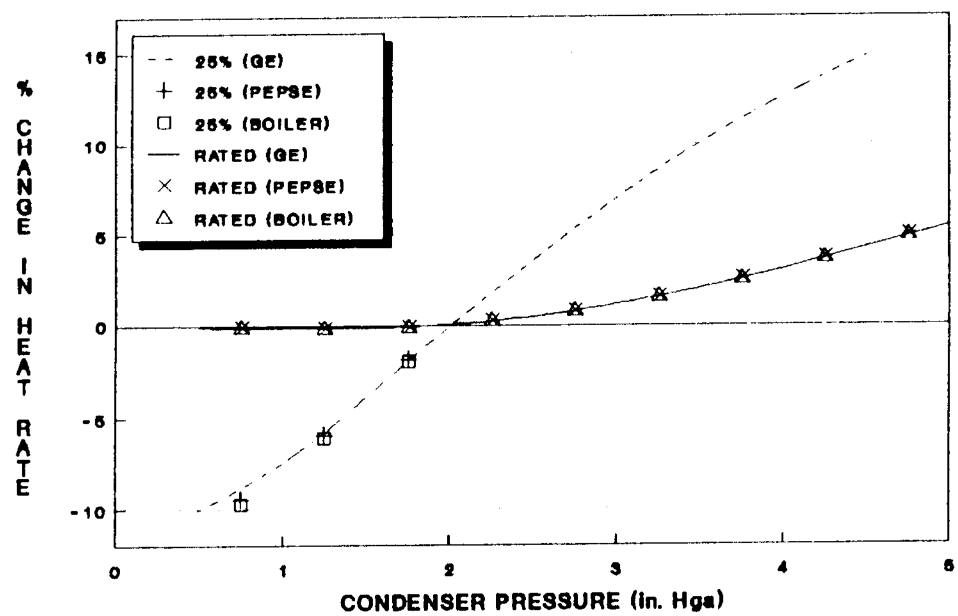
Throttle Temperature Correction Factors

Figure 11



Reheat Temperature Correction Factors

Figure 12



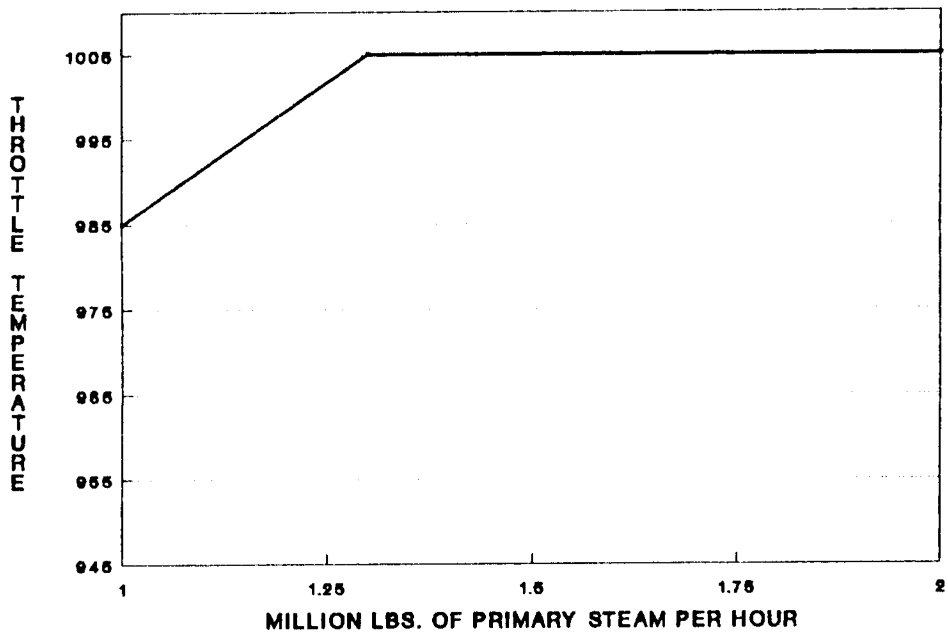
Exhaust Pressure Correction Factors

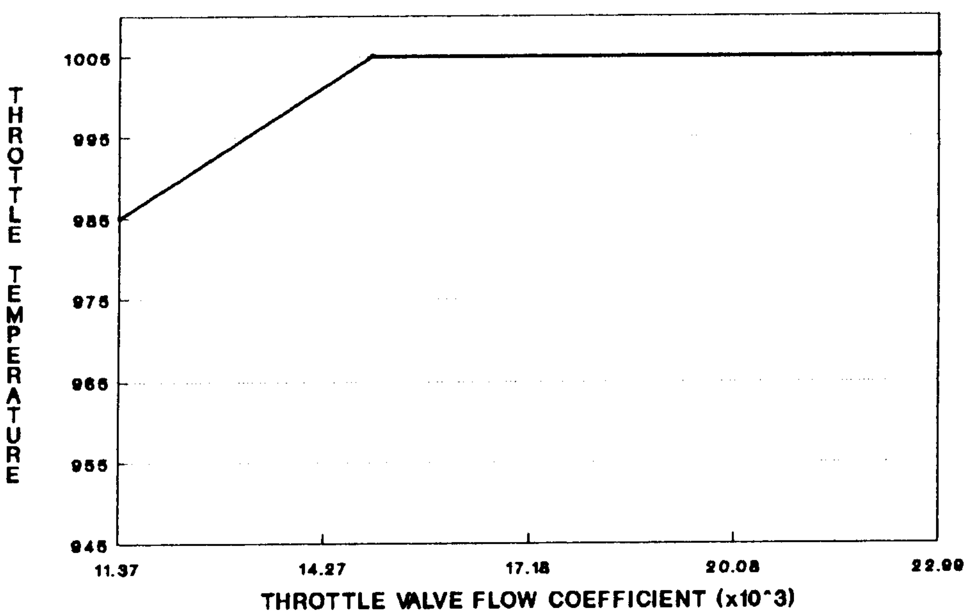
Figure 13

increases the mass flow rate. In addition, the target throttle flow cannot be calculated without knowing the target temperature, and the target temperature cannot be determined without knowing the flow.

The problem was overcome by converting the boiler manufacturer's primary steam flow versus throttle temperature curve to a throttle valve flow coefficient versus throttle temperature curve (Figure 14). This was done by solving the Simplified Martin's Formula for the flow coefficient (C) based on design pressure (p), the steam flow being converted (m), and a specific volume (v). The specific volume is calculated from the design pressure and the temperature corresponding to the steam flow being converted. Again, the temperature used was adjusted (reduced by five degrees) for heat loss between the boiler outlet and the turbine throttle valve.

Once the throttle valve flow coefficient versus throttle temperature curve has been programmed into the OLS software, a target flow for the given valve position can be calculated. The measured flow (m), measured throttle pressure (p), and a specific volume (v) based on measured throttle conditions can be used in the Simplified Martin's Formula to calculate a throttle valve flow coefficient (C). This flow coefficient can then be used to determine a boiler design throttle temperature from the flow coefficient versus throttle temperature curve. The Simplified Martin's Formula can then be used again to solve for target throttle flow (m) based on the design throttle pressure (p), the calculated throttle valve flow coefficient (C), and the design specific volume (v). In this instance, the specific volume is based on design throttle pressure and boiler design throttle temperature.





Controlled Throttle Temperature

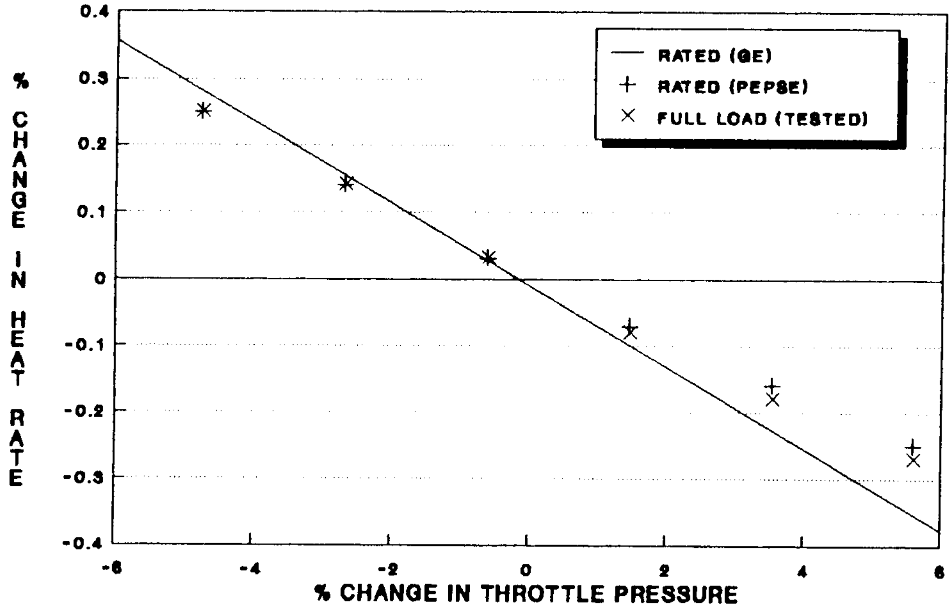
Figure 14

UPDATES BASED ON PERFORMANCE TEST RESULTS

The goals of the Santee Cooper performance testing program include a minimum of one turbine cycle performance test on each coal fired unit every year. In addition, a post outage turbine cycle test will be run on any unit that undergoes major turbine work. This schedule provides accurate trends of component degradation and evaluates improvements made during turbine outages. It is expected that the results of these tests can also be used to update and fine-tune the OLS calculations.

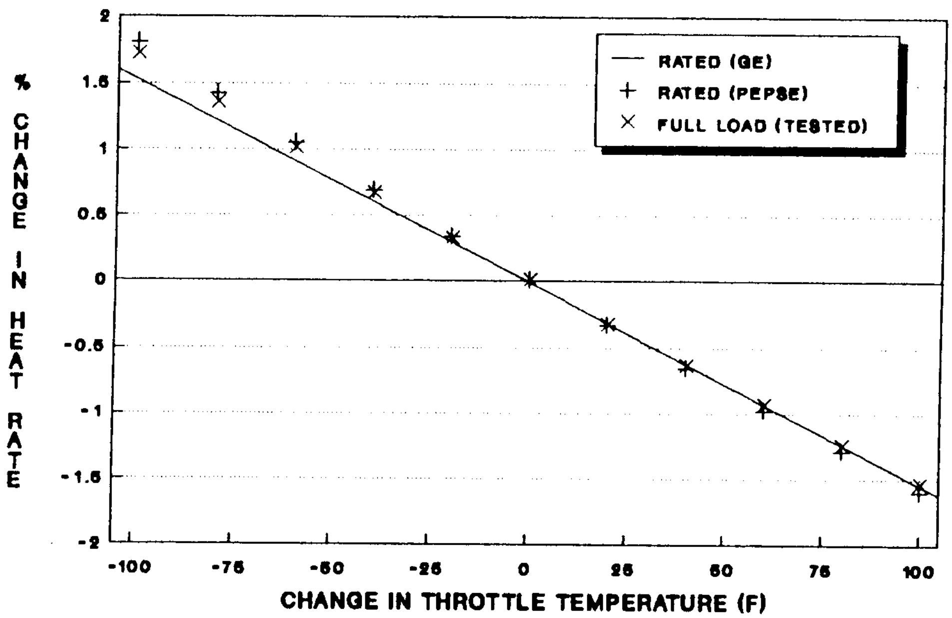
A VWO turbine test was run on Winyah Unit 1 in March, 1990. The PEPSE model resulting from this performance test was then used for controllable parameter sensitivity analysis. These sensitivity studies were run in the same manner as outlined in previous sections, with the exception of turbine solution methods. The turbine components were modeled as general turbines (Type 8) rather than GE turbines (Type 4 - 7). The solution method used was either efficiency and flow coefficient (IPCASE = 3) or efficiency and pressure ratio (IPCASE = 1). A straight line expansion (LINXP = 1 on card 70YYY8) was specified for the high pressure and combined intermediate and lower pressure turbine sections. Boiler design data was not included in this analysis.

The results of these sensitivity studies are presented in figures 15 through 18. Since the turbine performance test was only run at full load, low load comparisons can not be made at this time. Initial review of these figures indicates that turbine cycle degradation has a large impact on reheat temperature and exhaust pressure correction factors. However, further analysis shows these effects result from the turbine solution method. The Type 8 turbine solution methods chosen hold turbine efficiency constant, regardless of changes elsewhere in the system. The GE procedures produce small changes in turbine efficiency with changes in controllable parameters. Sensitivity studies run with turbine design data using Type 8 turbine solution methods result in correction curves very similar to those produced by the test data model. Therefore, the changes in correction



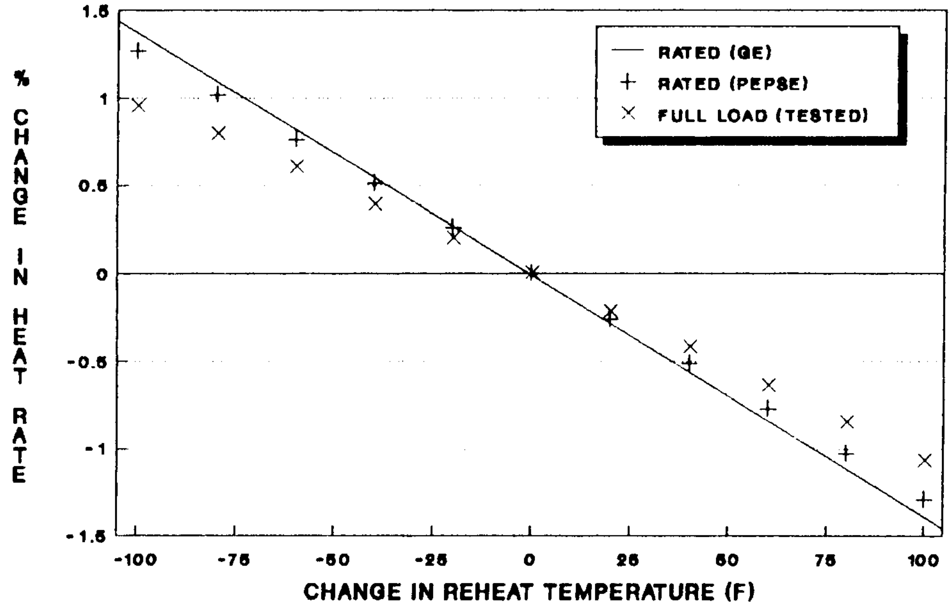
Throttle Pressure Correction Factors

Figure 15



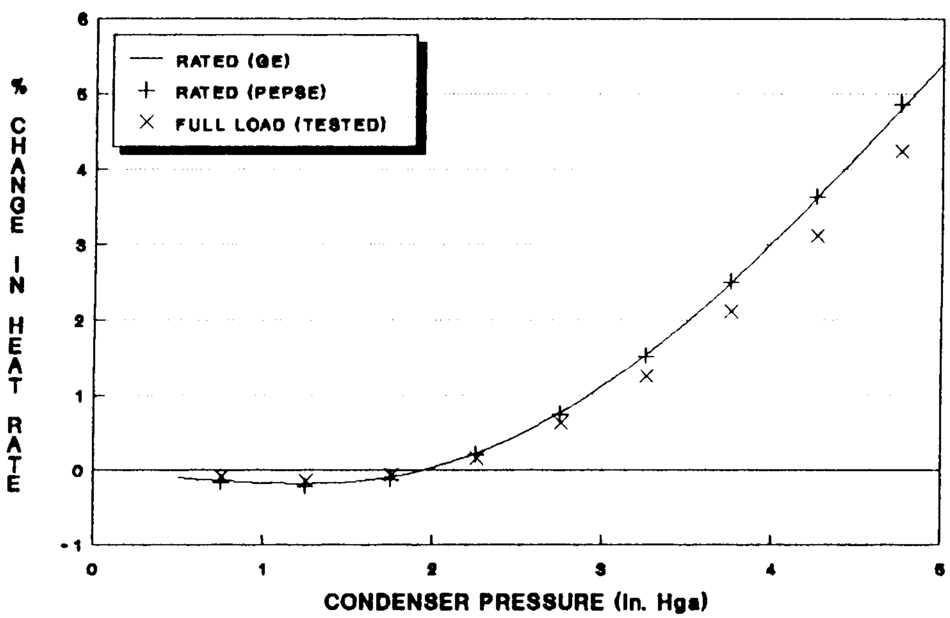
Throttle Temperature Correction Factors

Figure 16



Reheat Temperature Correction Factors

Figure 17



Exhaust Pressure Correction Factors

Figure 18

factors are not actually a result of component degradation but are a result of the change in turbine solution method.

Additional analysis is needed to determine the true effect of component degradation on controllable loss equations. Tests and analysis should be performed at valve points over the entire operating range of the unit to study the effects at lower loads. The sensitivity studies should use GE turbine solution procedures, modified to match test data through the use of efficiency multipliers and expansion line shapers. This should eliminate changes caused by the turbine solution method.

CONCLUSION

In summary, PEPSE can be used to provide accurate, plant specific heat rate correction factors for use in controllable loss monitoring systems. The GE supplied correction curves are generalized for all units of similar design and do not account for specific design differences. PEPSE models can be developed that provide plant specific response to variations in operating conditions and thus, a more accurate indication of controllable parameter heat rate effects.

Boiler design operating curves should be included in controllable loss analysis to provide achievable operating targets. The inclusion of this data only impacts the PEPSE results for throttle pressure and throttle temperature and then, only at low loads (below 75 percent in the case of Winyah 1). At higher loads, superheat sprays are the only parameter which differs between boiler design and turbine design, and they have an insignificant effect on the throttle pressure, throttle temperature, reheat temperature and condenser pressure sensitivity study results.

Finally, using performance test results to fine-tune controllable loss analyses appears to have an insignificant effect at full load. However, the turbine solution method does impact the reheat temperature and exhaust pressure correction curves. Additional testing and analysis needs to be performed to determine if component degradation has an effect on controllable loss sensitivity studies at lower loads. This analysis should include GE turbine procedures, modified to match test data, to account for changes in turbine efficiency caused by changes in boundary conditions.

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