Development of More Accurate Correction Factors Through Heat Balance Modeling

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ABSTRACT

On-line controllable loss monitoring systems require a method to calculate the heat rate and generation 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). However, these curves are typically very generic and do not include the effects of unique turbine cycle design characteristics. In addition, the response of a particular system to off-design controllable parameters may vary as the unit ages and the performance of individual cycle components begins to degrade. Therefore, using the correction curves provided by the turbine manufacturer may not provide the desired accuracy in many performance monitoring system applications.

This paper outlines a method to develop heat rate and generation correction curves for the primary controllable parameters through heat balance modeling. It will include plant specific curves developed using this method for the original design cycle configuration and a comparison with the curves provided by the original turbine manufacturer for units of varying size, vintage and supplier. In addition, it will include the results of studies performed to determine the impact of turbine cycle performance degradation on the plant specific correction curves.

INTRODUCTION

In the early 1980s, many utilities began aggressive programs to improve the operating performance of their power plants. One of the areas identified for improvement was reduction in operator controllable losses. Previously, operators had been trained to control unit boundary conditions to specific setpoints, but were unaware of the impact off-design operation had on the ultimate operating cost for the unit. In addition, the instrumentation and control technology available on older units made control to a specific setpoint very imprecise.

Subsequently, improved instrumentation and the replacement of antiquated control systems with state-of-the-art distributed control systems provided operators with the capability to more accurately control the unit to the design setpoints. In addition, many facilities included on-line performance monitoring systems in the control system upgrade which provided a near real-time indication of the costs associated with the off-design operation of the four primary turbine cycle controllable parameters (main steam pressure, main steam temperature, hot reheat temperature, and condenser pressure). With this improved control capability and improved operator awareness, utilities began making dramatic improvements in their system heat rates.

As system performance improves, aggressive utilities continue looking additional, although smaller magnitude, improvements in performance and more accurate methods for operating cost accounting. One area in which improvements in operating cost accounting can frequently be made is in the on-line calculation of the costs related to operator controllable losses.

Traditionally, on-line performance monitoring systems utilize turbine vendor supplied heat rate and generation deviation curves to calculate the losses associated with off-design operation. Detailed heat balance analysis indicates that the generic curves provided by the turbine manufacturer may not provide the accuracy many utilities desire. In the following sections of this paper, a method for developing plant specific deviation curves through heat balance modeling will be outlined, and the plant specific curves will be compared with the generic curves provided by the turbine vendor for accuracy. These analyses are based entirely upon turbine cycle response. Changes in boiler efficiency resulting from varying boundary conditions are not considered in these studies.

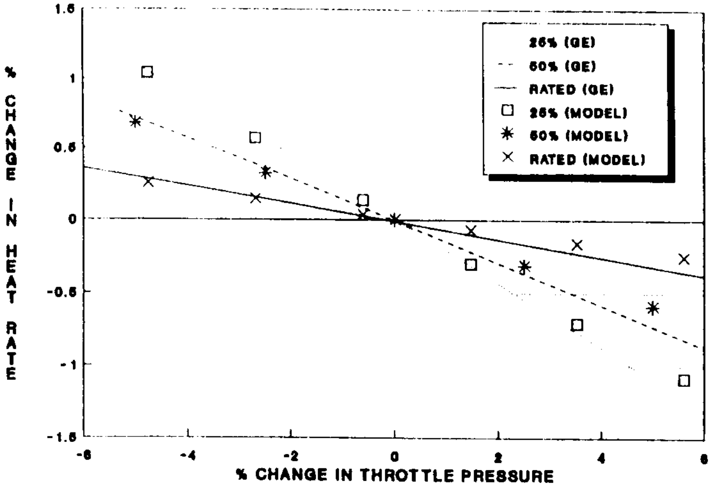
PEPSE® ANALYSIS

Since variations in turbine cycle boundary conditions cause changes in the performance of individual plant components, sensitivity studies performed on plant specific models must include a method to account for these performance changes. In particular, changes in turbine stage efficiencies resulting from changes in flow and backpressure must be accurately calculated. The vendor supplied correction curves also 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 a method to simulate a constant throttle valve position and calculate the change in cycle flow resulting from the variation in these boundary conditions.

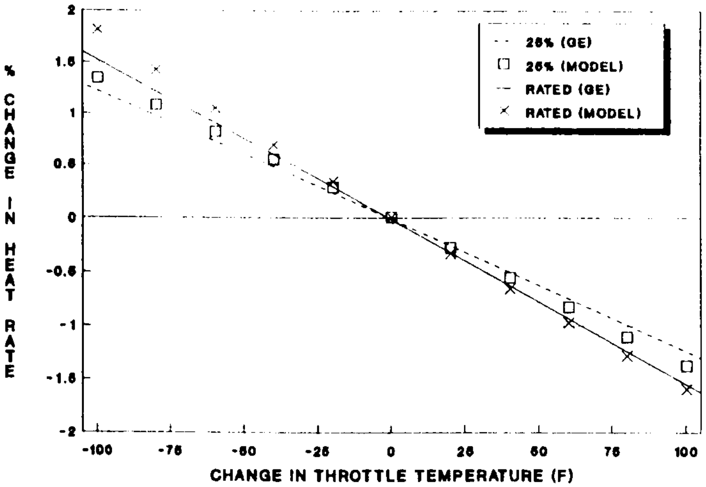
These sensitivity studies were performed on a turbine cycle model utilizing General Electric turbine solution procedures[1] (PEPSE turbine types 04 - 07) with all other components (condenser, feedwater heaters, etc.) in performance mode. Several PEPSE runs were then made while varying one controllable parameter through a specified range and holding all other boundary conditions constant. In addition, the sensitivity studies for throttle pressure and throttle temperature should include PEPSE's Special Option 1 to 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.

The ranges used for the sensitivity analyses were selected to ensure that the boundaries would not be exceeded during regular operation. The units were analyzed at 25 percent, 50 percent, 75 percent, 100 percent, and valves-wide-open (VWO) load points. Results from a previous study[2] indicated that the model-based analysis would, in-fact, produce results slightly different than the vendor supplied curves, as shown in Figures 1 through 4.

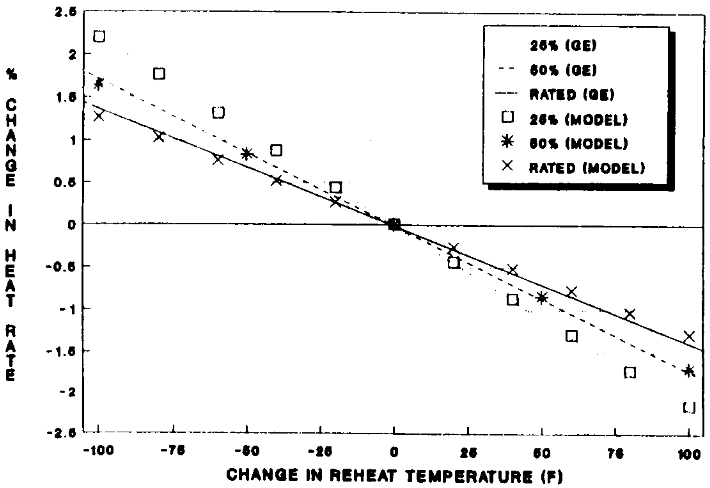
These figures present a comparison between the General Electric (GE) correction curves and the results of the PEPSE analyses for a 270 megawatt unit. The PEPSE generated points reproduce



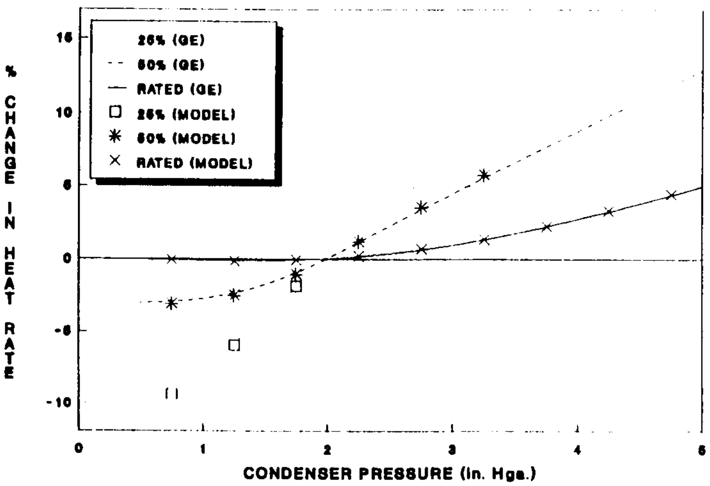
Throttle Pressure Correction Factors
Figure 1



Throttle Temperature Correction Factors
Figure 2



Reheat Temperature Correction Factors
Figure 3



Exhaust Pressure Correction Factors
Figure 4

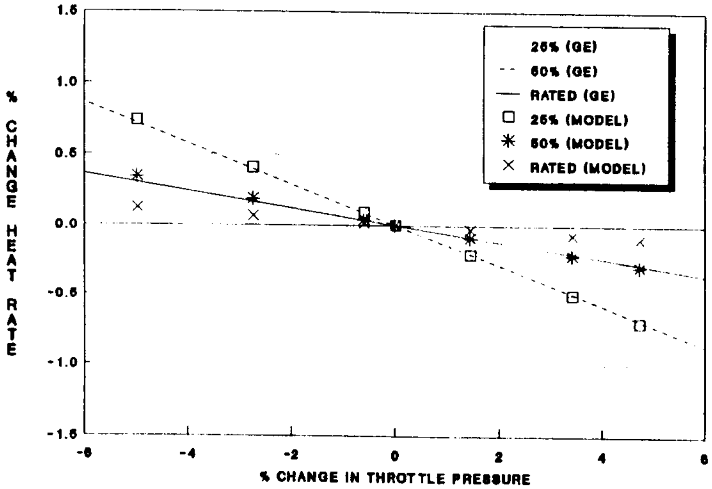
the GE curves very well for reheat temperature and condenser pressure. The results for throttle pressure and throttle temperature, however, show a slight difference between the design curves and the points calculated through PEPSE modeling. Analyses on several other GE turbine cycles indicates that the vendor supplied deviation curves for condenser pressure will always be consistent with the results of plant specific heat balance sensitivity studies, and this vendor supplied curve is unique for different turbine cycle designs. However, since the correction curves for throttle pressure, throttle temperature and reheat temperature are the same for all single reheat, subcritical pressure units, more accurate curves can be developed through plant specific heat balance sensitivity studies.

Further analyses were performed on units of varying size and units from other suppliers to study these differences in more detail. For these analyses, throttle temperature, throttle pressure and hot reheat temperature were varied from 90 percent to 105 percent of their design values at each load point. Condenser pressure effects on heat rate and generation were also studied in more detail, but, as previously mentioned, the model results compared very well with the vendor supplied curves. Therefore, the condenser pressure comparisons will not be presented in this paper.

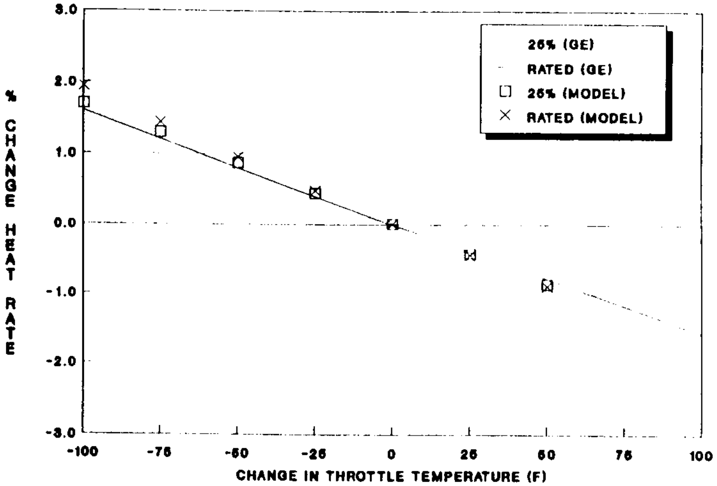
RESULTS FROM DESIGN PEPSE ANALYSIS

Figures 5 through 8 compare the controllable parameter deviation curves generated by the PEPSE model to the vendor supplied curves for a 427 megawatt General Electric subcritical turbine. In addition to size, this unit differs from the one described in the previous section in that it has 7 stages of feedwater heating versus six stages for the previously discussed unit, and it utilizes a steam driven boiler feed pump versus an electrical pump. These figures show an even greater difference between the PEPSE developed and vendor supplied curves than was evident in Figures 1 through 3.

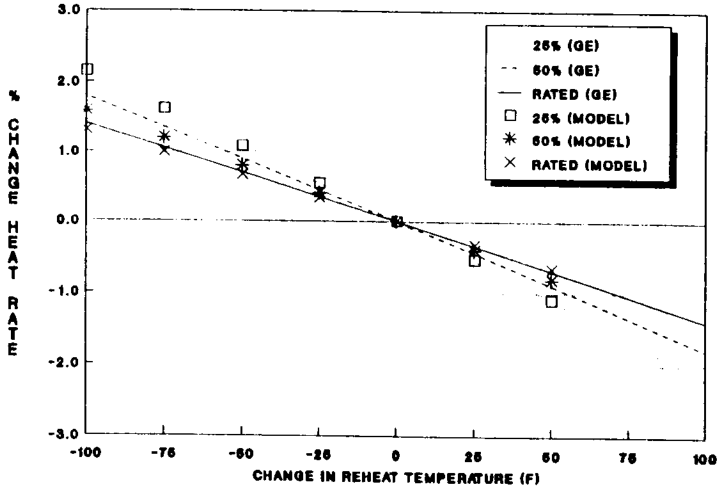
The heat rate and generation deviations due to off-design throttle pressure operation are particularly important for this utility, due to limited capacity and nearly continuous operation at



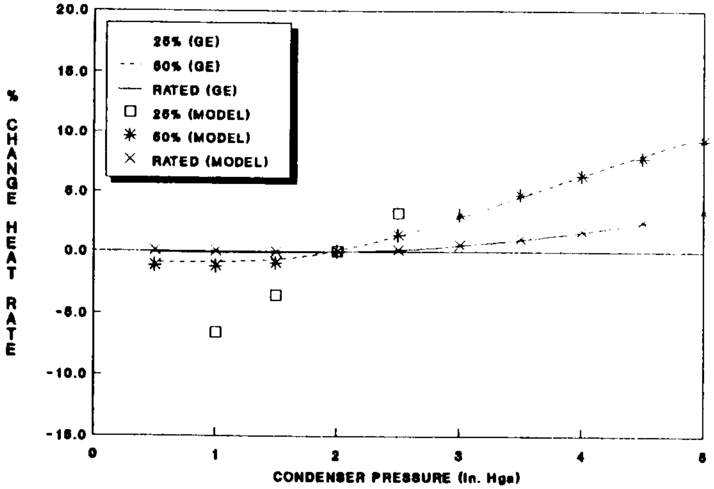
Throttle Pressure Correction Factors
Figure 5



Throttle Temperature Correction Factors
Figure 6



Reheat Temperature Correction Factors
Figure 7



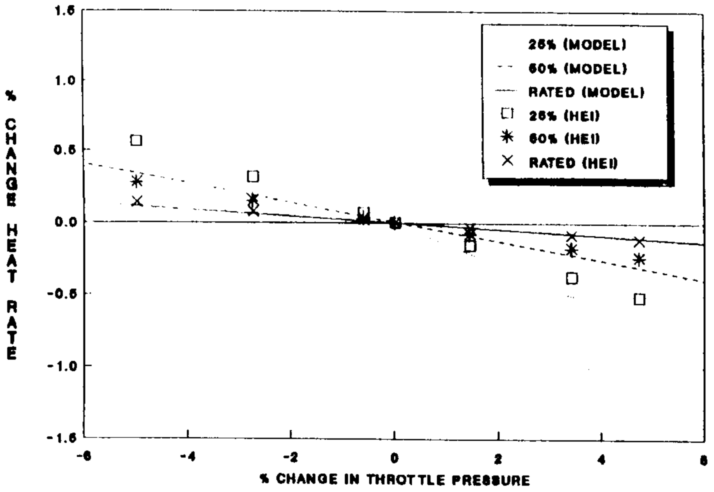
Exhaust Pressure Correction Factors
Figure 8

five percent overpressure for the unit being analyzed. The comparison presented in Figure 5 would indicate a difference in heat rate deviation of nearly 200 percent between the two methods of analysis. This large difference raised some concern about the accuracy of the PEPSE analysis. However, confidence in the modeling technique was reaffirmed by the vendor supplied five percent overpressure heat balance. This heat balance showed that the heat rate decrease at five percent overpressure should be 8 BTU/kw-hr as calculated by the model, rather than the 24 BTU/kw-hr calculated using the vendor supplied curve. Therefore, an economic analysis comparing operating cost savings through reduced heat rate versus maintenance cost increases due to continuous operation at five percent overpressure would provide erroneous results if the vendor supplied curve was used.

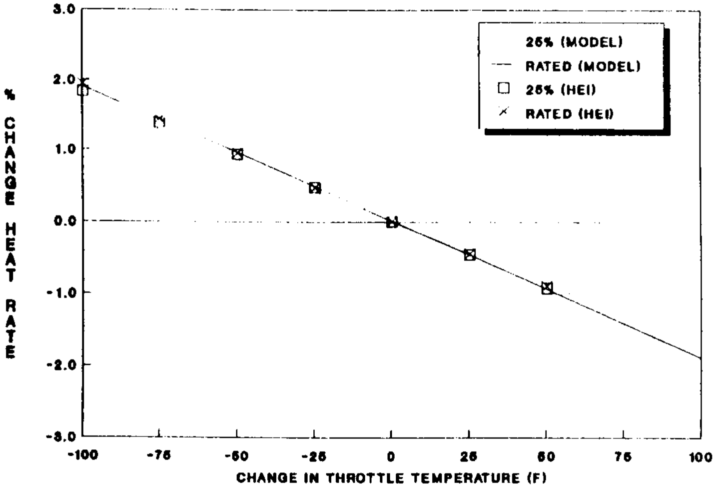
The substantial differences between the vendor supplied curves and the PEPSE generated deviations in this case are primarily caused by the turbine-driven boiler feedpump. As mentioned previously, the 270 megawatt unit had an electrically-driven feedpump. GE does not include electrically-driven pumping power in their calculation of heat rate, or in developing the heat rate effect curves. However, the required pumping power and change in pumping power resulting from throttle pressure variations is implicitly included in the heat rate calculation when the unit contains a turbine-driven feedpump. Since the GE supplied heat rate deviation curves are identical for both of these units, they cannot account for the impact of the turbine-driven feedpump.

RESULTS FROM PEPSE ANALYSES INCLUDING HEI CONDENSER CALCULATIONS

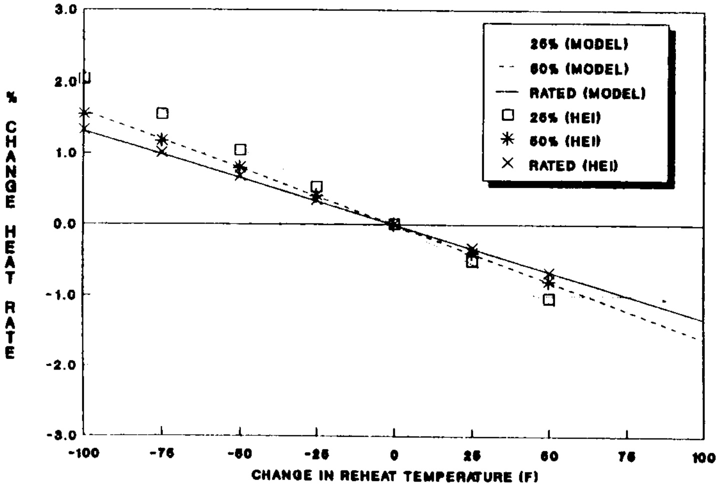
The 427 megawatt GE unit utilizes a cooling tower to achieve desired circulating water conditions. However, the cooling tower does not have sufficient capacity to maintain design condenser pressure during the summer months. Therefore, in a effort to provide heat rate deviation curves that more accurately represented true plant operation, a condenser model that utilized the Heat Exchange Institute (HEI) standards for condenser pressure calculations was included in the overall turbine cycle model. As sensitivity studies were then performed, the circulating water inlet temperature and flow was held constant and condenser pressure was



Throttle Pressure Correction Factors
Figure 9



Throttle Temperature Correction Factors
Figure 10



Reheat Temperature Correction Factors
Figure 11

allowed to vary with changes in shell-side inlet conditions. Figures 9 through 11 show a comparison of the heat rate deviation curves generated with a constant 2.0 in. Hga. condenser pressure to heat rate deviation values calculated where the circulating water conditions were held constant and condenser pressure was allowed to vary.

These figures show that both methods provide very similar results, with the exception of the throttle pressure correction factors at 25 percent load. Since this unit is virtually never run below 50 percent load, it was determined that the effects of varying backpressure could be ignored in the development of design-basis heat rate correction curves.

CORRECTION CURVES WITH COMPONENT PERFORMANCE DEGRADATION

An aggressive performance testing program is critical to optimize plant performance and plan for major unit outages. This testing program should be complimentary to a utilities on-line performance monitoring program and visa-versa. The results of highly accurate performance tests and special tests, such as N2 leakage tests, can be used to fine tune an on-line performance monitoring system, and the trends produced by the performance monitoring system can provide valuable input for scheduling performance tests and diagnosing test results.

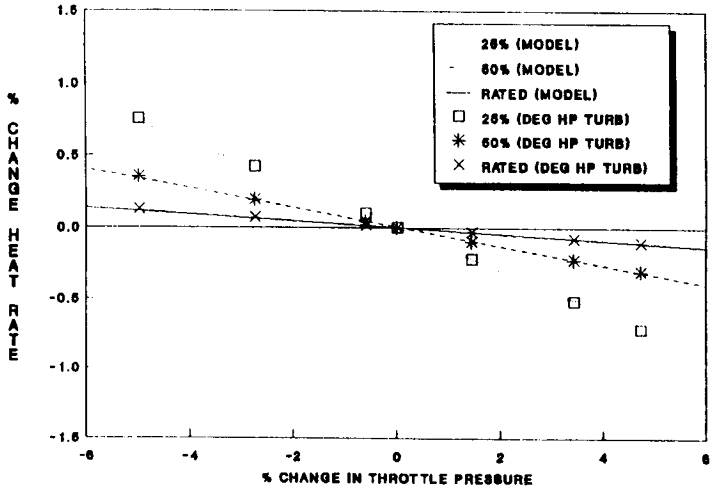
In a previous study[2] analyses were performed to evaluate the effects of component degradation on controllable parameter heat rate correction factors. The results of this study were inconclusive, because the calculational methods used were thought to be incorrect. Therefore, further analyses to evaluate the effects of component degradation on heat rate correction curves were performed on the 427 megawatt GE turbine cycle that was used in the studies discussed above.

In these analyses, major turbine components (the high pressure turbine section, the intermediate pressure turbine section, the low pressure feedwater heater train, and the high pressure feedwater heater train) were artificially degraded to assess the impact on the PEPSE generated correction factors. In the previous study, turbine efficiencies were decreased, but then held constant for the sensitivity studies. It was noted that the efficiencies should change with variations in boundary conditions. Therefore, the analyses performed on the 427 megawatt unit utilized the GE 2007C procedures to calculate turbine section efficiencies, then the overall section efficiency was varied by applying a multiplier (PEPSE's EFMULT) to the calculated efficiency. Intermediate extraction conditions could then be calculated by utilizing the GE 2007C procedures to determine the expansion line shape. These analyses used the PEPSE default value for SHAPER to determine the expansion line shape.

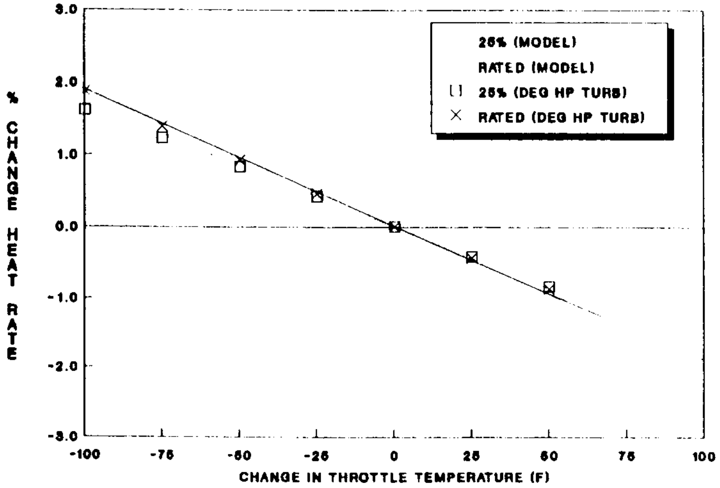
In the first study, the high pressure turbine section efficiency was degraded by five percent from design (i.e., EFMULT = 0.95). The results of this study are presented in Figures 12 through 14. It can be seen from these figures that the high pressure turbine degradation has virtually no impact on the correction factors. The results were basically the same whether the condenser pressure was held constant or an HEI condenser calculation was used with circulating water inlet conditions being held constant.

In the second study, the intermediate pressure turbine section efficiency was degraded by five percent from design. The results of this study are presented in Figures 15 through 17. The degraded intermediate turbine efficiency did have a larger impact than the degraded high pressure turbine efficiency. The deviations were, once again, particularly evident at low loads, and could produce correction factors with differences as high a ten percent. Therefore, if a utility is seeking extremely accurate loss accounting, fine-tuning correction curves for degraded intermediate pressure turbine performance may be worth considering. As with the high pressure turbine degradation study, the intermediate pressure turbine degradation results were basically the same whether the condenser pressure was held constant or an HEI condenser calculation was used with circulating water inlet conditions being held constant.

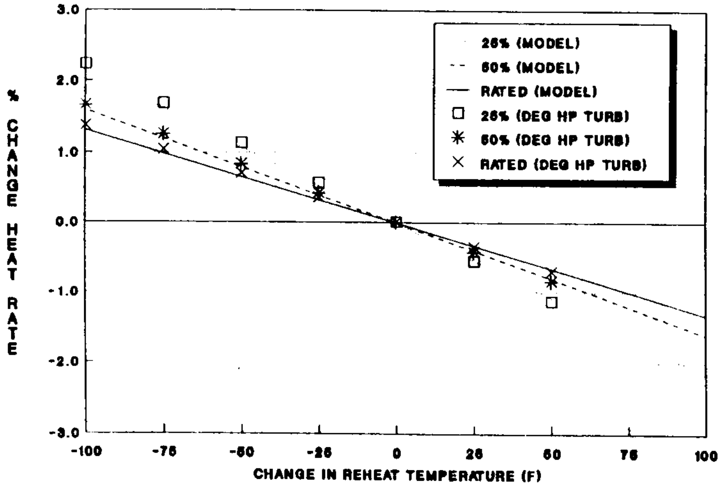
In the third and fourth studies, the terminal temperature differences (TTDs) for the low pressure and high pressure feedwater heaters were degraded by five degrees fahrenheit. As can be seen in Figures 18 through 23, feedwater heater performance has no impact on the turbine cycle heat rate correction factors.



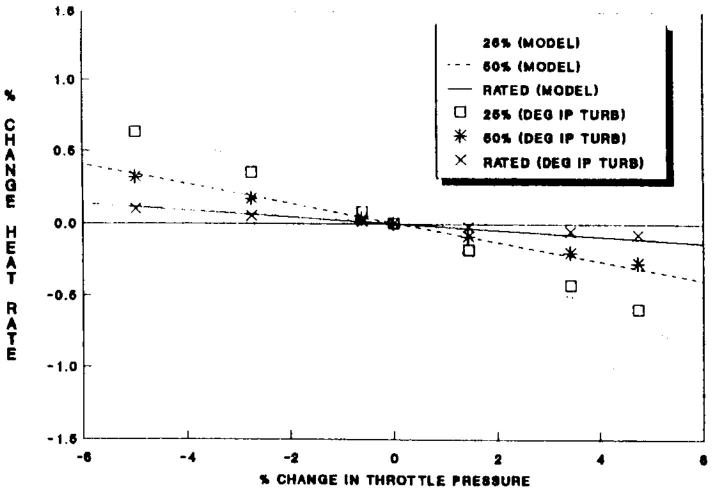
Throttle Pressure Correction Factors
Figure 12



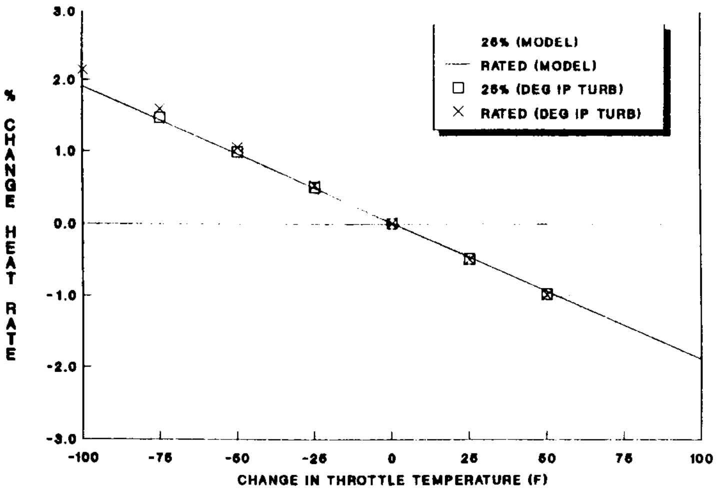
Throttle Temperature Correction Factors
Figure 13



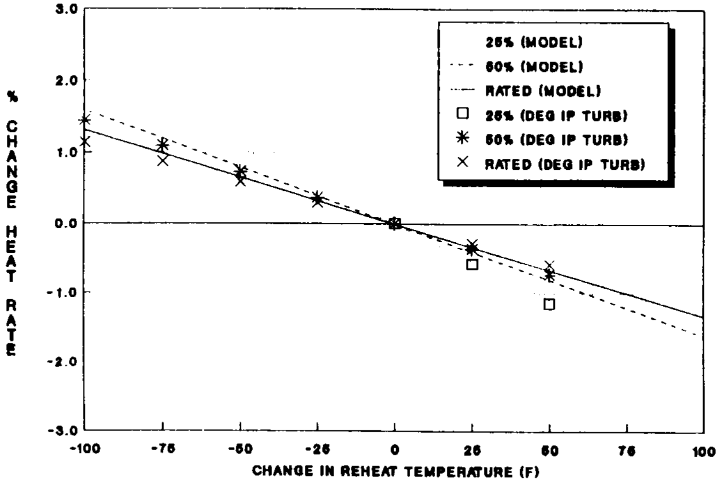
Reheat Temperature Correction Factors
Figure 14



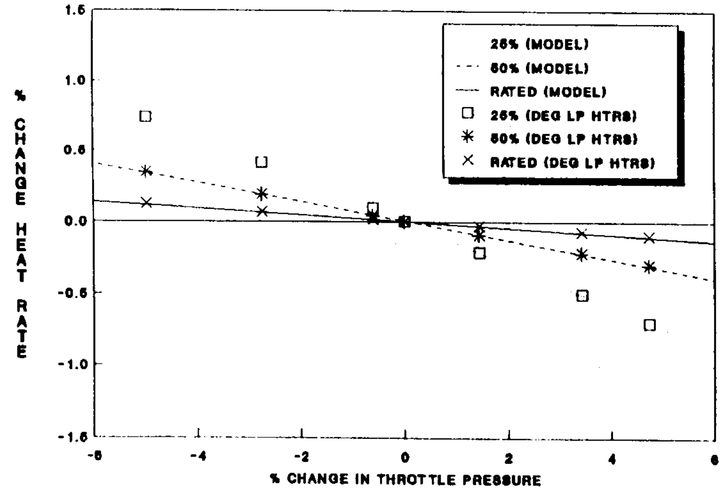
Throttle Pressure Correction Factors
Figure 15



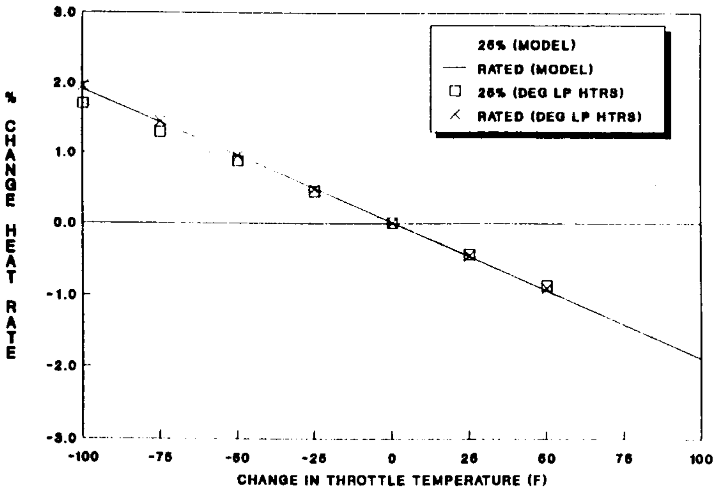
Throttle Temperature Correction Factors
Figure 16



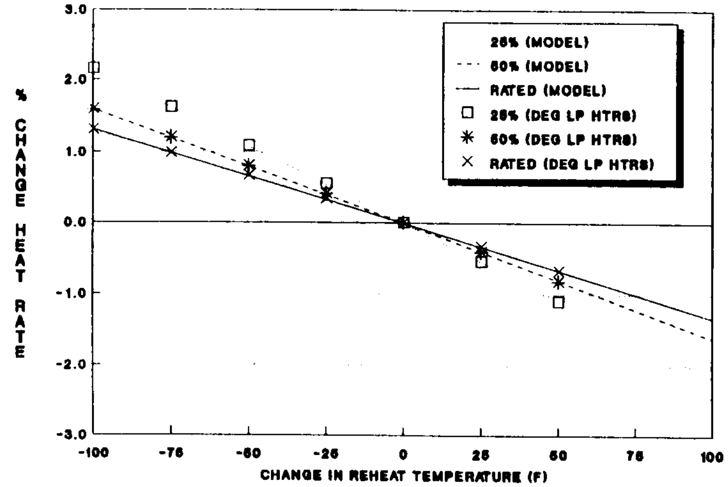
Reheat Temperature Correction Factors
Figure 17



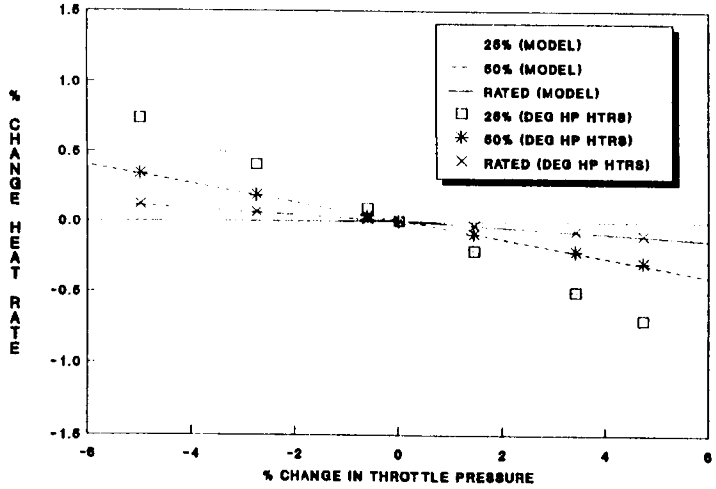
Throttle Pressure Correction Factors
Figure 18



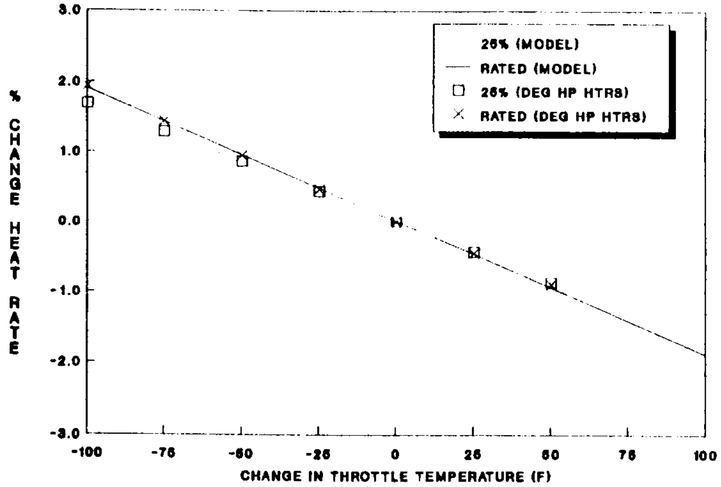
Throttle Temperature Correction Factors
Figure 19



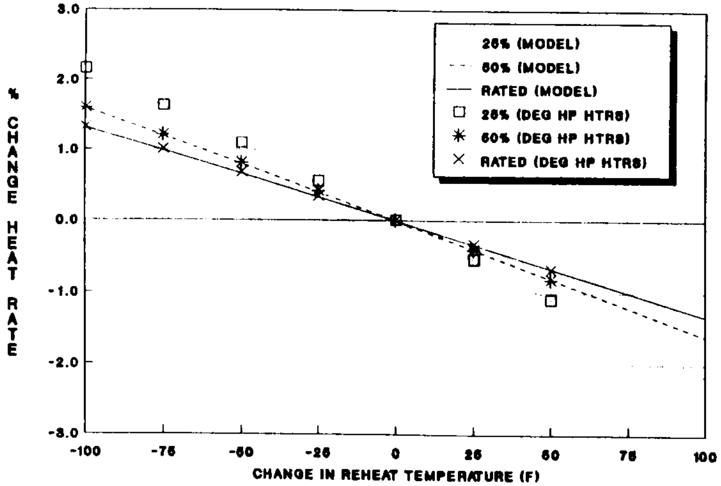
Reheat Temperature Correction Factors
Figure 20



Throttle Pressure Correction Factors
Figure 21



Throttle Temperature Correction Factors
Figure 22



Reheat Temperature Correction Factors
Figure 23

OTHER FACTORS TO CONSIDER

The studies discussed in this paper are based entirely on turbine cycle analysis. The curves presented do not consider any deviations in boiler performance or necessary changes in control parameter targets based the boiler manufacturer's operating limits. Although reference 2 showed that the changes in controllable parameter setpoints imposed by the boiler manufacturer did not significantly impact the heat rate correction factors for a 270 megawatt GE turbine cycle with an electrically-driven feedpump, the impact may be different for a unit with a turbine-driven feedpump. Either way, setting achievable targets is critical if an on-line monitoring system is going to be effective, and accurately implementing correction factor curves with varying controllable parameter targets requires the use of an independent variable that is truly independent of the boundary conditions, such as throttle valve flow coefficient.

In addition, many of the studies performed for this paper would have an impact on boiler performance and unit heat rate. For instance, although degraded high pressure turbine performance had very little impact on the turbine cycle heat rate correction curves, the turbine degradation would result in off-design cold reheat steam conditions and probably effect boiler efficiency and reheat spray requirements. Therefore, the assumptions used in generating correction factors should be acknowledged and documented.

CONCLUSIONS

Heat balance models can provide accurate, plant specific heat rate correction factors for use in controllable loss monitoring systems. The vendor supplied correction curves are generalized for all units of similar design and do not account for specific design differences. In particular, the vendor supplied curves can provide very erroneous correction factors for units with turbine-driven feedpumps.

Turbine cycle component degradation, with the exception of intermediate turbine section efficiency, appears to have a very minimal impact on heat rate correction factors for throttle pressure, throttle temperature, reheat temperature, or condenser pressure. Therefore, plant specific heat balance models should be developed to produce accurate controllable parameter correction factors, if a utility is seeking accurate, on-line accounting of system losses. However, it is not critical to fine-tune these correction factors as turbine cycle components degrade, unless the degradation is extreme.

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