Thermal Performance Evaluation and Assessment of Steam Turbine Units

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INTRODUCTION

The power generation business is becoming increasingly competitive and the need to reduce and manage operating costs has become considerably more important. Improvements in thermal performance can help power plant operators gain a competitive advantage by lowering operation costs and increasing plant output. Therefore, any reduction in a unit's thermal performance due to equipment deterioration, damage or operation is of critical importance. Performance degradation is often an excellent indicator of the types of problems occurring within the equipment. Proper analysis of thermal performance degradation can lead to an early identification of the cause. Remedial action can then be taken before the problem reaches a magnitude where it can seriously damage the equipment, result in a forced outage or require an extended repair outage.

The optimum level of thermal performance for a turbine-generator unit and its feedwater cycle can best be achieved and maintained by an ongoing program to evaluate and assess performance. Performance monitoring activities have a three-fold purpose:

- Detect deterioration in the thermal performance by trending changes in various performance parameters
- Identify by proper data evaluation and interpretation the cause of performance degradation
- Develop cost-effective solutions to correct operational and equipment problems that contribute to the degradation in thermal performance

For the turbine owner, this monitoring can result in more cost-effective maintenance through proper unit selection, outage cycle planning and parts planning based on identifying the turbine section experiencing the major loss. To meet these objectives, a thermal performance monitoring program should include the following essential features:

- Periodic acquisition of performance data
- Correct evaluation of the data
- Diagnosis of problems through interpretation of results

- Inspection and restoration of the turbine steam path

This paper identifies testing procedures and monitoring activities which are effective for obtaining and evaluating performance data. This data, with its associated results, will establish accurate trends of various performance characteristics. The basic theory of the turbine steam-path flow, pressure and temperature relationships is reviewed to improve understanding of how these trends can be interpreted and used to locate and identify the cause of the turbine deterioration. Some common causes of turbine deterioration are deposits, solid particle erosion, increased clearance in packings and tip spill strips, and foreign object damage.

This paper also demonstrates the value of conducting a turbine steam path evaluation to identify the specific components contributing to the thermal performance loss. In addition, this inspection can be used to verify the predictions of turbine conditions from the monitoring program.

MEASUREMENTS REQUIRED FOR MONITORING PERFORMANCE

The value of the performance test data analysis greatly depends on the quality of the data. The use of "Acceptance" test procedures, such as ASME PTC-6 and PTC-6.1, to obtain periodic performance results yields the most accurate test data for analysis and evaluation. However, Acceptance test procedures generally are too expensive for use in periodic monitoring of performance trends. Fortunately, performance monitoring does not necessarily require absolute accuracy, but it demands repeatable data for establishing accurate trends of various performance characteristics.

ASME PTC-6S Test

The ANSI/ASME PTC-6S Report, "Simplified Procedures for Routine Performance Tests of Steam Turbines,"[1] provides guidance in devel-

oping procedures to monitor performance. This procedure provides the necessary data to determine turbine cycle heat rate, kilowatt capacity, HP and IP section efficiencies, turbine stage pressures and low capacities.

The essential measurements for an ASME PTC-6S test are shown in Figure 1. For this test, like other heat rate tests, the most important measurements are electrical load and primary flow, which is usually measured in the feedwater line. To ensure repeatability, the differential pressure transducer on the primary flow element should be calibrated prior to the test. In addition, station watt-hour meters usually have to be read by counting disk revolutions to obtain a precise reading of kilowatt output. Temperatures and pressures at the inlet and outlet of the HP and IP sections should be made with instruments capable of producing high repeatability.

The repeatable determination of the turbine cycle heat rate also depends on cycle isolation. Since primary flow is measured in the feedwater line, any leakage between the flow measurement and the turbine stop valve must be eliminated or the test results adjusted accordingly. Otherwise, an erroneous measurement of heat rate will be obtained. Steam and water leakages within the turbine cycle do not affect the measurement of heat rate, but these leakages can cause a significant loss in the heat rate and kilowatt capacity.

Capacity Test

When a repeatable measurement of primary flow cannot be obtained, another practical, effective method of trending the performance of the turbine-generator unit is to make periodic measurements with the turbine control valves wide open (VWO). This test, usually referred to as a Capacity test, determines the generator output, HP and IP enthalpy drop efficiency, turbine stage pressures and flow capacity.

In rare cases, when steam generator capacity may be inadequate to drive the unit to a VWO position at rated pressure, one alternative is to reduce pressure to permit opening all inlet control valves. This procedure is preferred over the more depending method of accurately reproducing positions of partially opened control valves or for correcting results for valve position.

Figure 2 is a schematic flow diagram for a typical reheat unit with the final feedwater heater at the cold reheat point. This diagram identifies the measurements to be made in a Capacity test
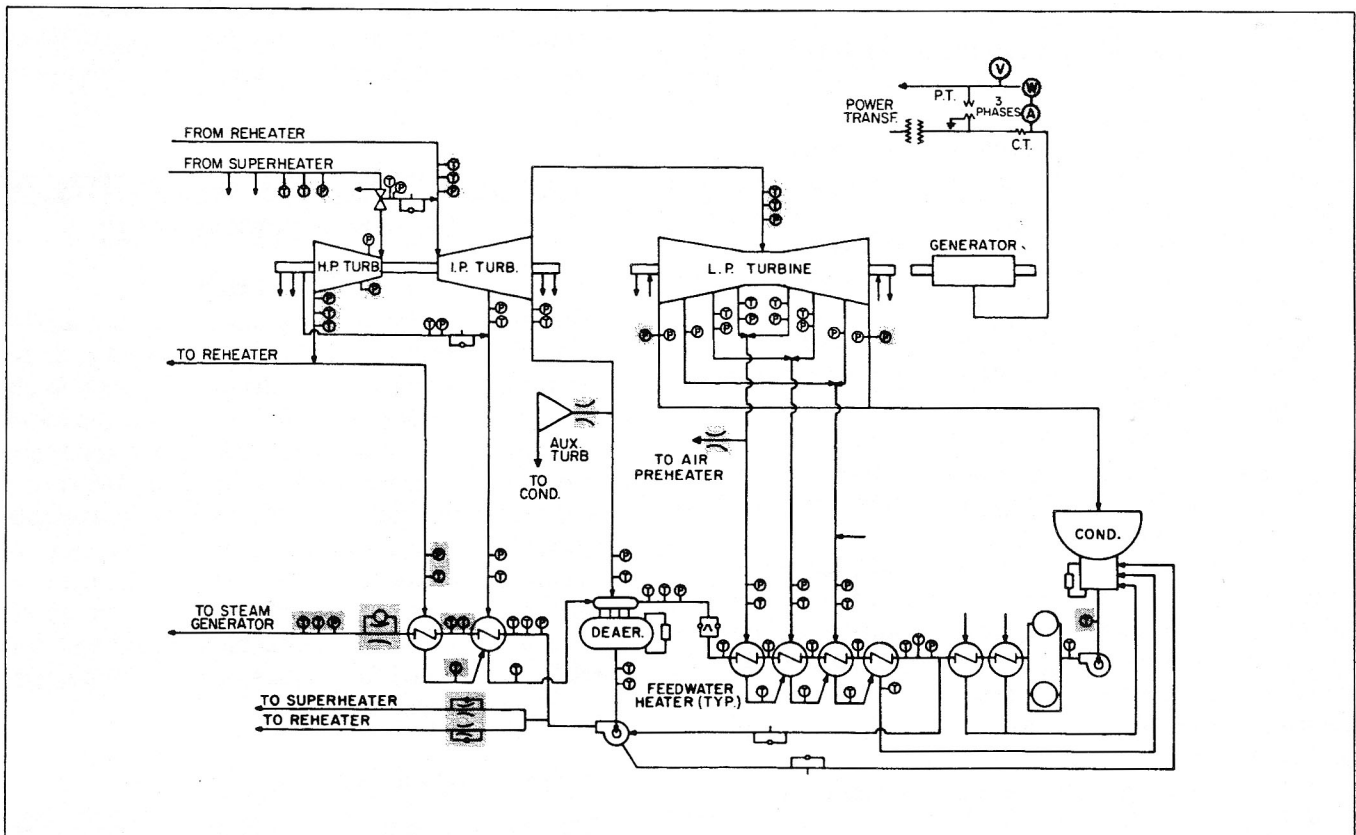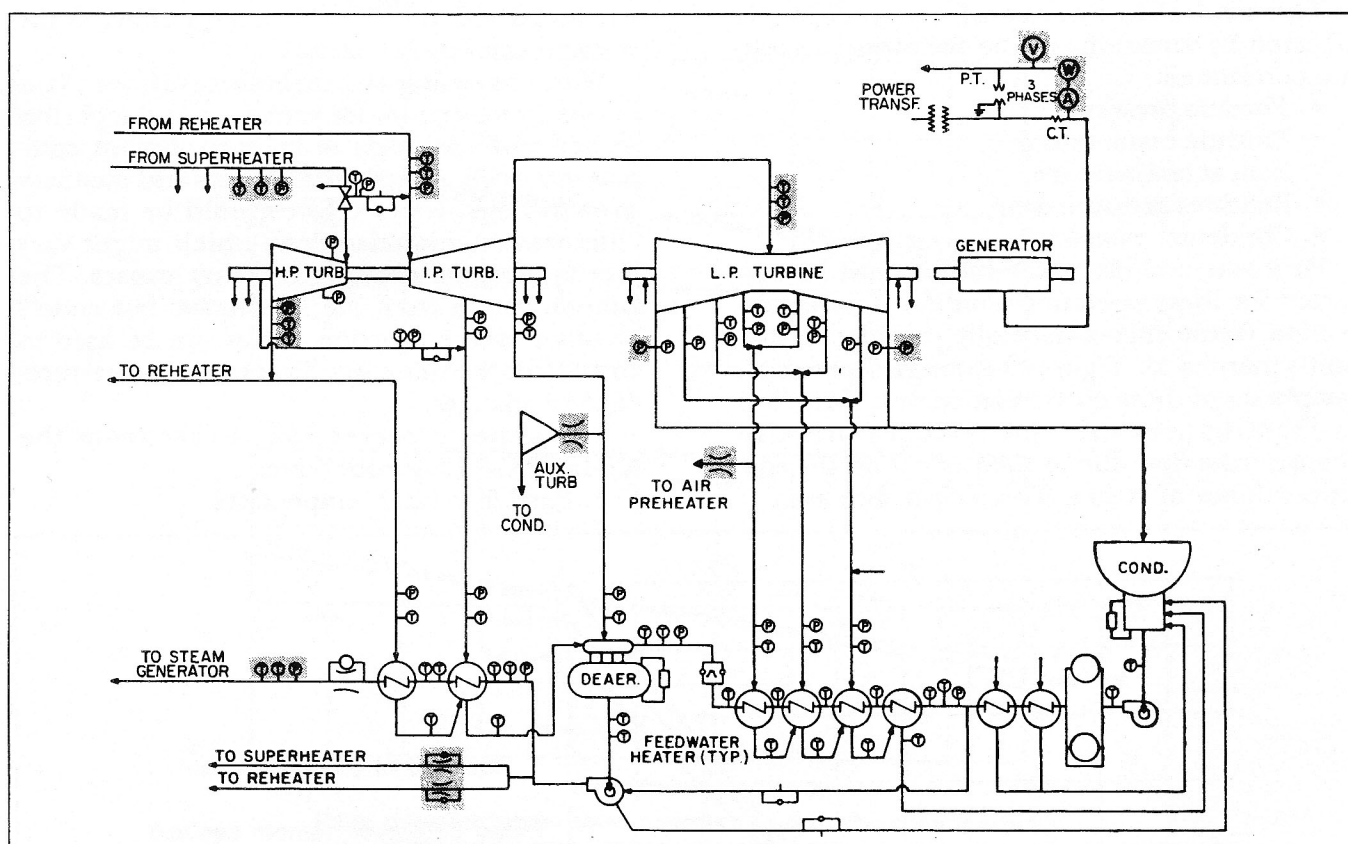

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Figure 1. Test instrumentation location for PTC 6S test — fossil

Figure 2. Test instrumentation location for Capacity test — fossil

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for establishing accurate trends of various performance characteristics.

The Capacity test, like the simplified heat rate test, depends on repeatable measurements of electrical output and the pressures and temperatures at the inlet and outlet of the HP and IP turbine sections. Isolation of the turbine cycle is also important because it can significantly affect the electrical output of the unit.

Enthalpy Drop Test

The Enthalpy Drop test is used frequently for monitoring steam turbines. This test involves a minimum number of instruments, but establishes the efficiency of those turbine sections most susceptible to deterioration. An Enthalpy Drop test can be conducted on any turbine section operating entirely in the superheat region, such as the HP and IP sections of fossil reheat units and the HP section of automatic extraction units. The pressure and temperature ahead of and at the exhaust of the section being tested must be measured. The efficiency of the section can then be calculated from the ratio of actual to isentropic enthalpy drop.

EVALUATION OF PERFORMANCE DATA

The effort of obtaining good repeatable test data will be wasted unless that data is properly evaluated. The generator output and turbine cycle heat rate depend on the operating conditions of the turbine cycle and the performance of the many individual equipment components. If the test results indicate that heat rate has deteriorated or the maximum electrical capacity of the unit has changed, any of the following conditions could be contributing factors:
- Turbine steam flow
- Efficiency of the turbine steam path
- Available energy of the turbine (i.e., steam conditions)
- Performance and operation of the balance-of-plant components

To assess the turbine condition and its contribution to any deterioration in thermal performance, output and heat rate must be corrected for the influence of two non-turbine related factors: the available energy of the turbine and the performance and operation of the balance-of-plant components.

The available energy of the turbine is affected by variations in the following operating conditions:

- Throttle pressure
- Throttle temperature
- Reheat temperature
- Reheater pressure drop
- Condenser vacuum

Heat rate and electrical output must be corrected for these operating conditions using correction factor curves normally provided in the unit's thermal kit. Figures 3 through 7 present a sample set of these correction curves. Variations in throttle pressure and temperature also change mass flow due to their effect on the specific volume of steam. This effect, however, is combined with the available energy effect in the relevant correction factors.

When assessing the turbine condition, it is necessary to account for variations in the performance and operation of balance-of-plant components, such as feedwater heaters and auxiliary process flows. Every effort should be made to eliminate or minimize flows which might vary due to seasonal changes or other causes. The generic curves from the Alternative test code[2] or other valid correction curves can be used to correct for the more significant cycle or balance-of-plant changes.

The generic correction curves from the ASME PTC-6.1 test code[2] are:

- Final feedwater temperature
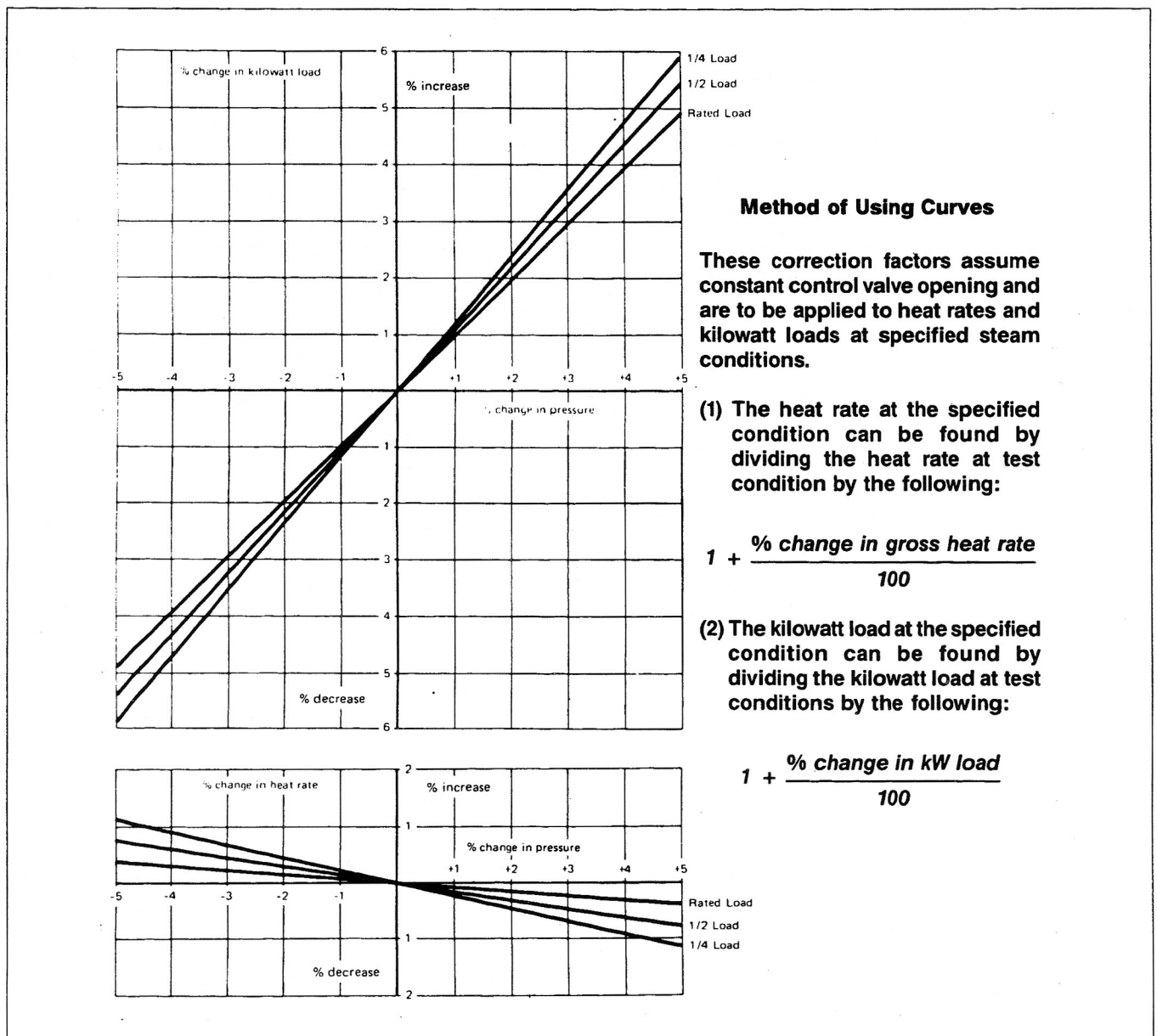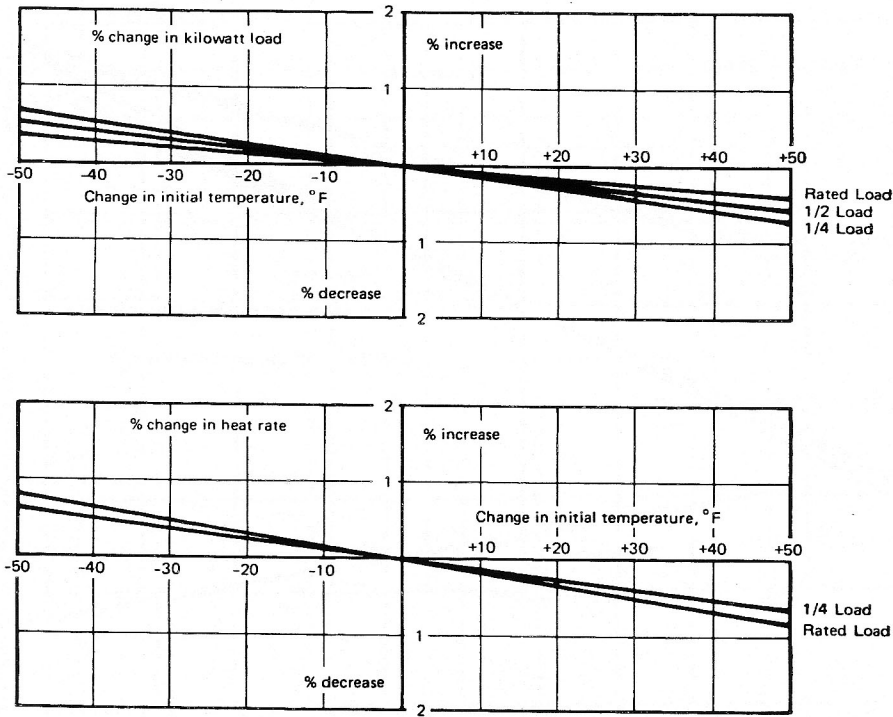

Method of Using Curves

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

(1) The heat rate at the specified condition can be found by dividing the heat rate at test condition by the following:

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

(2) The kilowatt load at the specified condition can be found by dividing the kilowatt load at test conditions by the following:

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

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Figure 3. Throttle pressure correction factors for single reheat units

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Method of Using Curves

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

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Figure 4. Throttle temperature correction factors for single reheat — subcritical pressure units

- Auxiliary extractions
- Main steam attemperation
- Reheat steam attemperation
- Condensate sub-cooling
- Condenser make-up

Occasionally, it may be necessary to make corrections for out-of-service feedwater heaters or for cycle leakages. These effects can best be calculated by heat balance calculations, but often can be adequately estimated by simplified calculations which consider first order effects. A rigorous program should be in place to identify, quantify and eliminate cycle leakages because they typically affect the thermal performance of the plant by more than 1% during normal operation.

Once these corrections have been made, the trend in heat rate and/or generator output can be used to assess the turbine condition. Steam flow and steam turbine efficiency are the two relevant factors which must now be considered. If the efficiencies of the superheated turbine sections have been established, a change in efficiency can be expressed in terms of a change in heat rate and generator output. Some typical values for the percent change in heat rate for a 1% change in section efficiencies for a single reheat unit are:

HP turbine	=	0.17
IP turbine	=	0.12 to 0.25
IP and LP turbine	=	0.72
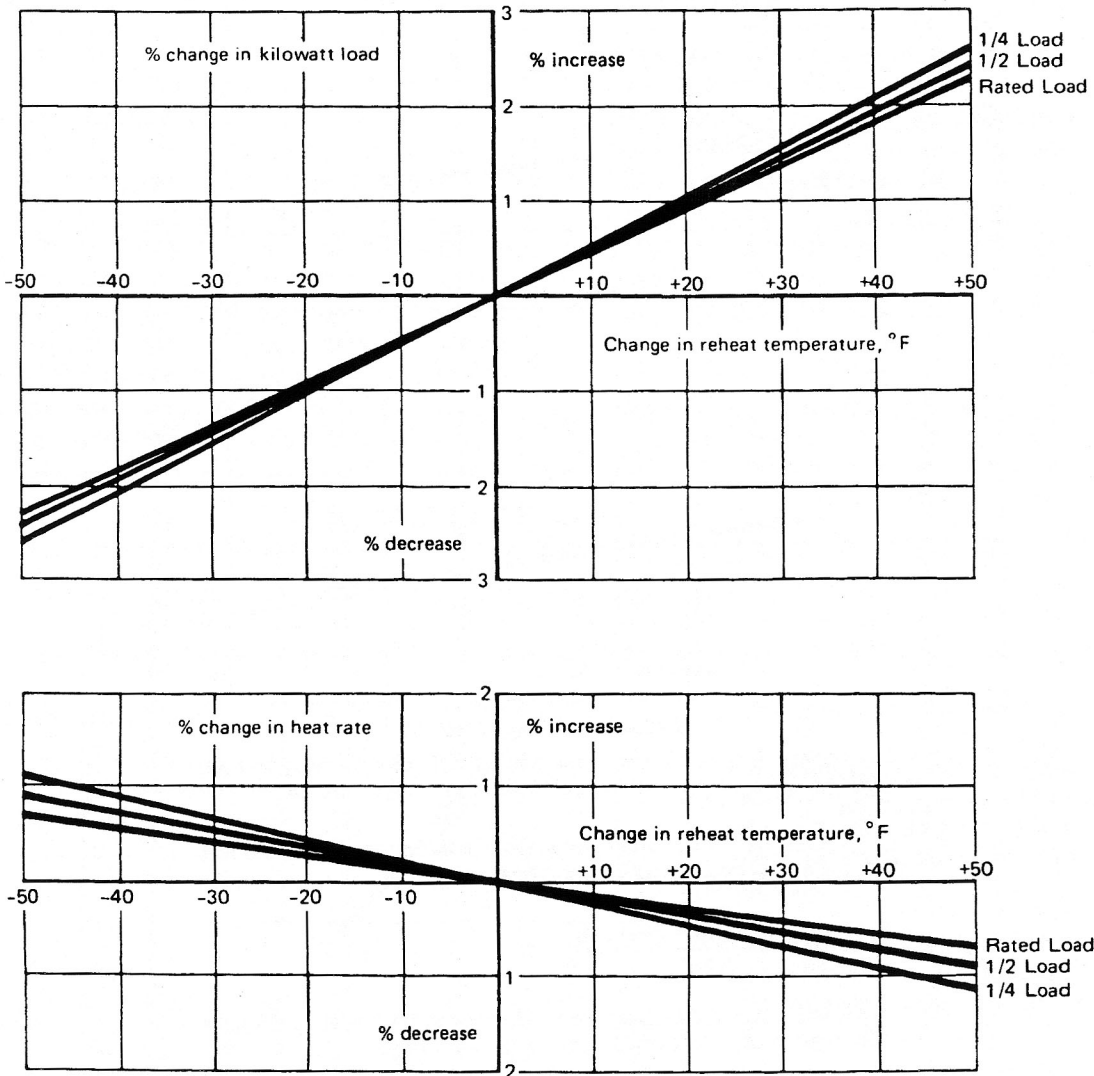
Method of Using Curves

These correction factors assume constant control valve opening and are to be applied to heat rates and kilowatt loads at specified steam conditions.
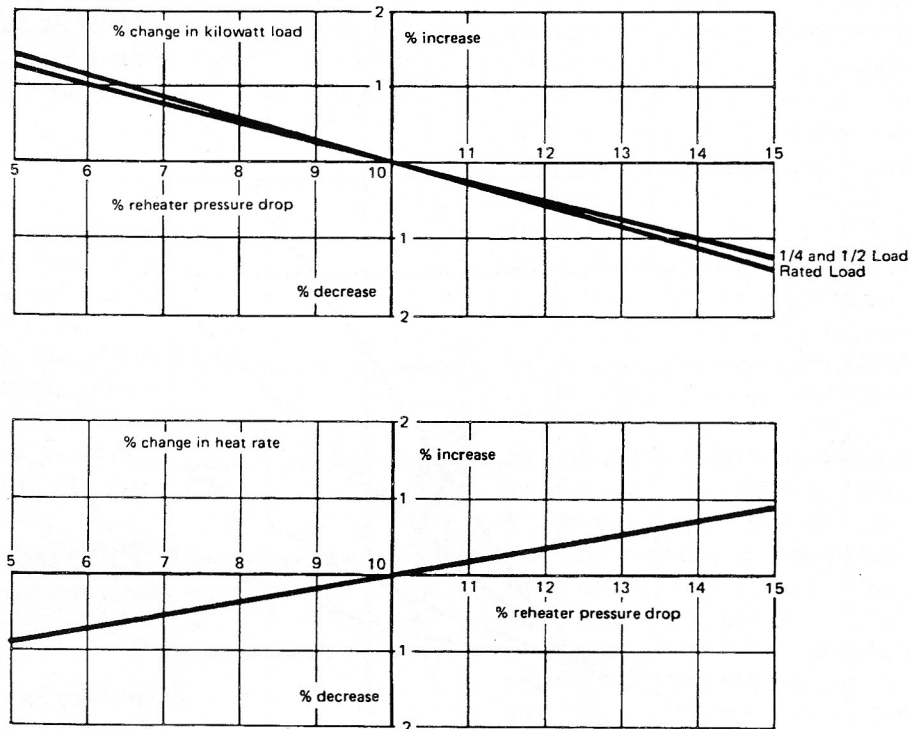
(1) The heat rate at the specified condition can be found by dividing the heat rate at test conditions by the following:

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

(2) The kilowatt load at the specified condition can be found by dividing the kilowatt load at test conditions by the following:

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

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Figure 5. Reheat temperature correction factors for single reheat units

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Method of Using Curves

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

(1) The heat rate at the specified condition can be found by dividing the heat rate at test conditions by the following:

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

(2) The kilowatt load at the specified condition can be found by dividing the kilowatt load at test conditions by the following:

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

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Figure 6. Reheater pressure drop correction factors for single reheat units

For non-reheat and industrial turbines with more than one turbine section, the effect on overall performance due to a change in the efficiency of one section can be estimated by multiplying that change by the proportion of total unit power produced in that section.
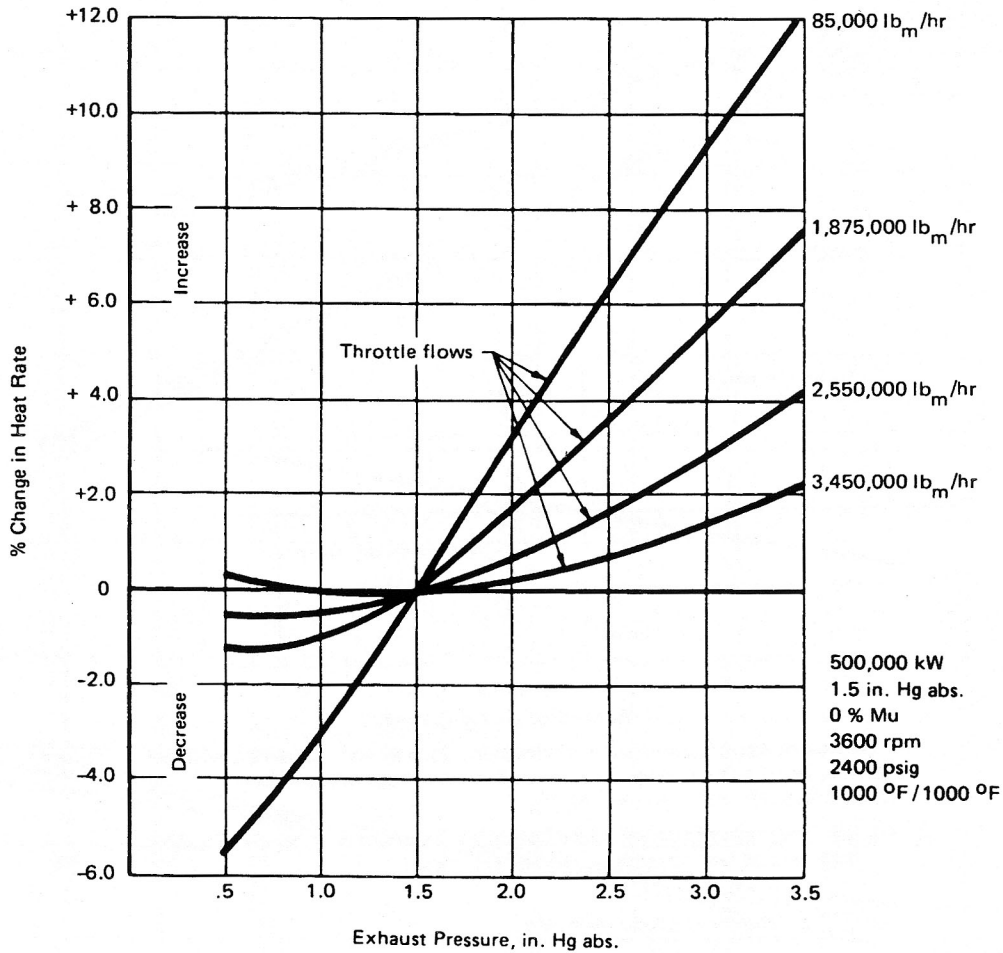
INTERPRETATION OF TURBINE TEST RESULTS

The proper interpretation of test results can lead to an assessment of the internal condition of the turbine which can assist in prioritizing maintenance activities. There may be indications of mechanical damage in a turbine section,

deposits or solid particle erosion. Knowledge of the turbine characteristics is necessary to understand why the performance has changed.

Maximum generator output is directly affected by changes in the efficiencies of the various turbine sections and changes in the flow capacity of the first three or four stages of the high-pressure turbine. Changes in the flow capacity of following stages may indicate a physical change in the steam path and consequential effects on local steam-path efficiency. A change in the flow capacity of the turbine or the flow capacity of a particular turbine stage is reflected in the stage pressure, temperature and flow relationship. Section 6 of the ASME PTC-6S Report

+12.0   85,000 lb$_m$/hr

+10.0

+ 8.0

+ 6.0   1,875,000 lb$_m$/hr

Throttle flows

+ 4.0   2,550,000 lb$_m$/hr

+2.0   3,450,000 lb$_m$/hr

0

-2.0   500,000 kW
1.5 in. Hg abs.
0 % Mu
3600 rpm
-4.0   2400 psig
1000 °F / 1000 °F

-6.0
    .5   1.0   1.5   2.0   2.5   3.0   3.5

Exhaust Pressure, in. Hg abs.

Method of Using Curves

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 1.5 in. Hg abs., 0% MU.

(1) The heat rate at the specified condition can be found by dividing the heat rate at test conditions by the following:

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

(2) The kilowatt load at the specified condition can be found by dividing the load at test conditions by the following:

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

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Figure 7. Exhaust pressure correction factor

contains a detailed discussion of these turbine characteristics. For all turbine stages, except the first and last, the stage pressure ratios are essentially constant and the basic flow equation simplifies to:

$$W = KAC_q \sqrt{P/v} \qquad (1)$$

where:

W = Flow to the following stage
K = A constant
A = Nozzle area
   = Coefficient of discharge
P = Inlet stage pressure
v = Specific volume at stage inlet

The equation can be rearranged as:

$$W/\sqrt{P/v} = KAC_q \qquad (2)$$

From the equation of state of an ideal gas $(Pv = RT)$, the equation can be arranged as:

$$W/P \, 1/RxT = KAC_q \qquad (3)$$

where:

R = Universal gas constant
T = Inlet stage temperature

This equation states that the flow function $(W/\sqrt{P/v})$ is related to the flow passage area of the stage (A) and the design and condition of the stage passage (C_q). In more general terms, the flow function relates to the steam path con-

dition. If a particular stage flow function has changed, then the downstream condition of the turbine steam path must have changed. This is a more powerful diagnostic tool in identifying damage, deposits, erosion or other problems which have affected a group of stages within the turbine steam path. If the effective flow area of a stage increases due to erosion or other problems, the flow function will also increase. Some problems, such as deposits, cause a reduction in the effective area of the stage and a corresponding decrease in the flow function.

The flow function can be used to recognize that a change has occurred in the effective area of the stage. However, the flow function is not proportional to the area change as implied in the equation. It is important to note that the derivation of the flow function equation is based on a constant pressure ratio across the stage. When the effective flow area of a stage changes, the stage pressure ratio also changes. Thus, the relationship of the flow capacity to nozzle area is somewhat more complex. Figure 8 shows the flow capacity change that can be expected for a change in nozzle area of an impulse-type turbine. For example, a 10% reduction in the stage 1 nozzle area would reduce the maximum capacity of the unit by about 3%.
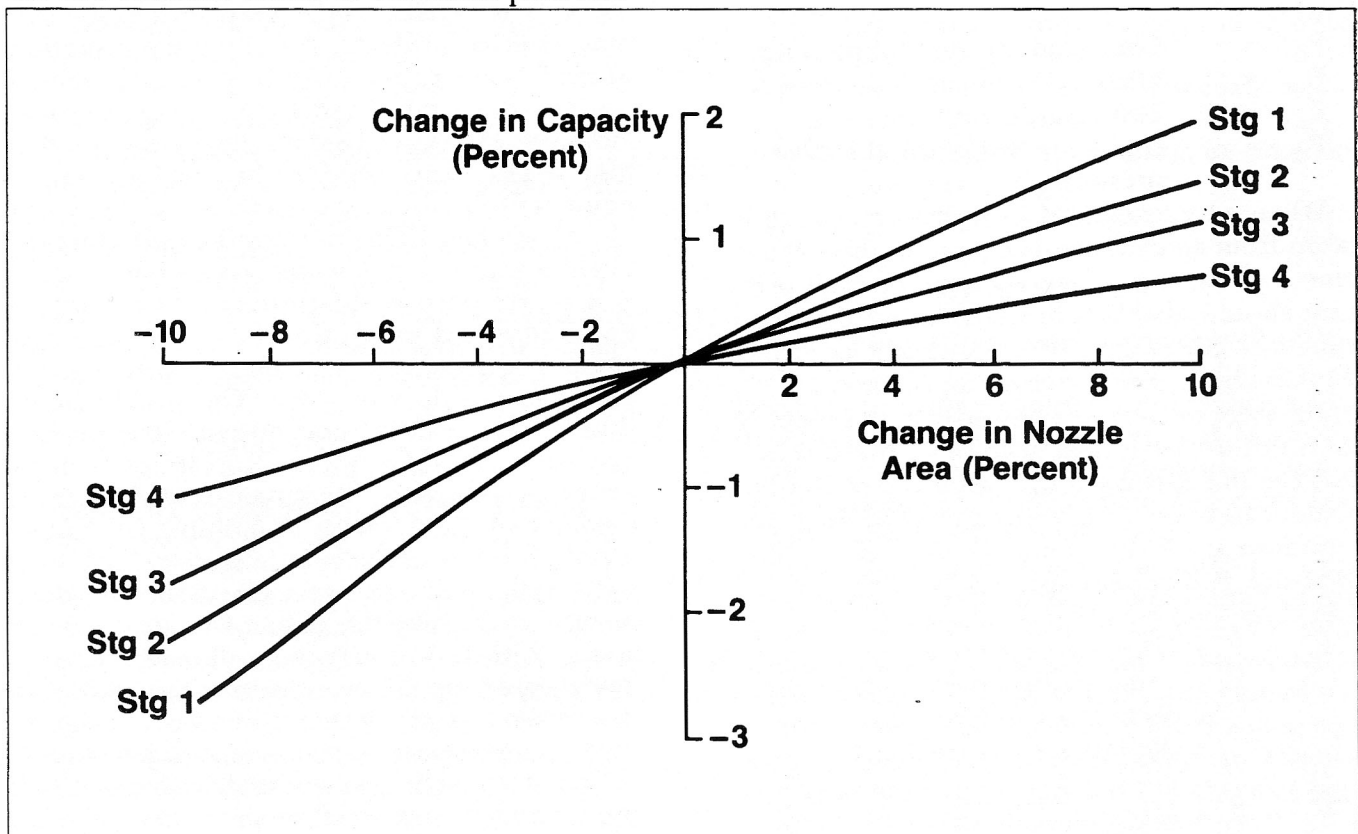

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Figure 8. Effect of change in nozzle area on flow capacity for impulse-type turbines

Since the Capacity test does not provide a repeatable measure of the primary steam flow, the flow function cannot be calculated.

Two options are available.

One is to use the relative condition function described in the paper, "Theory and Practice of Maintaining Steam Turbine Thermal Performance."[3]

The second option is to trend turbine stage pressures. As shown by equation 1, the steam flow divided by the absolute pressure ahead of a stage is proportional to the effective area of the following stage, provided that the temperature remains constant. For a constant valve position and constant inlet steam conditions, a change in a turbine stage pressure indicates either a change in the effective area downstream of the stage or a change in the flow capacity of the unit.

To use the trend of turbine stage pressures to predict the internal condition of the turbine, the stage pressures during the test must be corrected to reference steam conditions. The stage 1 pressure observed during a test on the HP section of a reheat turbine, or the pressure for any stage on a non-reheat turbine, should be corrected to reference conditions by the following equation:

$$P_c = P_o \times P_d / P_t$$

where:

P_c = Corrected pressure for plotting
P_o = Measured stage or shell pressure
P_t = Test throttle pressure
P_d = Design, or reference, throttle pressure

When an extraction for feedwater heating is taken from an intermediate stage in the HP turbine section, the measured stage or shell pressure should also be corrected using the same equation. Although not theoretically accurate, this correction is a very close approximation.

For stage or shell test pressures at or following the inlet to the reheat section of the turbine, and for the exit from the last stage of the HP section, additional corrections must be made for variations in throttle temperature, reheat temperature and reheat spray flow to the boiler. The correction equation to be used is:

$$P_c = P_o \times \text{(Throttle pressure and temperature correction)}$$
$$\times \text{(Reheat temperature correction)}$$
$$\times \text{(Reheat spray correction)}$$

$$P_c = P_o \times \sqrt{((P_d \times v_t)/(P_t \times v_d))}$$
$$\times \sqrt{(v_{dr}/v_{tr}) \times (1 - W_{rhs}/W_{rhb})}$$

where:

v_d = Design, or reference, throttle specific volume
v_t = Test throttle specific volume
v_{tr} = Specific volume at test temperature and test pressure at inlet to intercept valves
v_{dr} = Specific volume at design reheat temperature and test pressure at inlet to intercept valves
W_{rhs} = Reheat spray flow to the boiler
W_{rhb} = Reheat bowl flow

Once the turbine stage pressures are standardized, the percent difference from a reference or design value should be calculated. Then the values can be plotted vs. chronological test dates, as shown in Figure 9. The percent change in other performance parameters such as heat rate, generator output, section efficiencies, flow function, etc., can all be plotted on similar graphs.

TURBINE STEAM PATH EVALUATION

The interpretation of performance monitoring activity results can be used to identify turbine internal problems causing a deterioration in performance, and assist in planning maintenance required to address the problems. However, to restore performance during a turbine maintenance outage, the turbine components contributing to the performance loss need to be identified. This can best be done by conducting a turbine steam path evaluation.

A steam path evaluation should include a detailed visual inspection of the steam path components and clearance measurements of the packings and tip spill strips. The visual inspection should evaluate and quantify the performance impact of degradation effects such as erosion, deposits, damage, peening, etc. Clearance measurements at multiple circumferential positions of the diaphragm packings, tip radial spill strips and end shaft packings should be used to quantify the effect of increased clearances. With this information, decisions can be made based on the economics associated with the repair and replacement of turbine components, and the priority of necessary repair work.

The steam-path evaluation should categorize the identified stage performance losses into six components:
• Excess diaphragm packing leakage loss
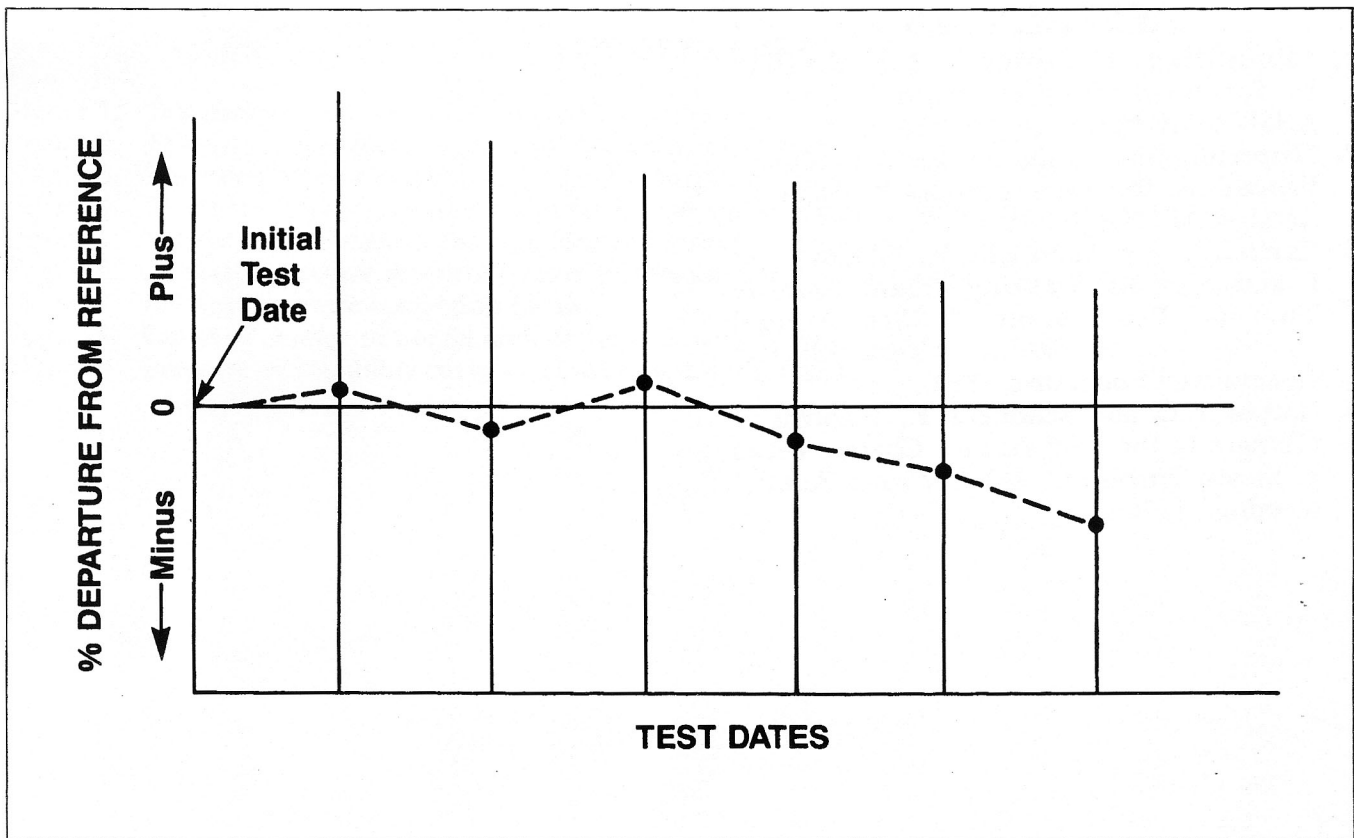
Figure 9. Pressure or capability curve vs. chronological test dates

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- Excess radial tip spill strip leakage loss
- Nozzle recoverable losses
- Nozzle unrecoverable losses
- Bucket recoverable losses
- Bucket unrecoverable losses

Recoverable losses are defined as those that can be recovered by cleaning, dressing and repair of the components, or replacement of clearance controls. The unrecoverable loss is that part of the performance loss that can only be recovered by replacement with new components, such as new diaphragms or buckets.

PERFORMANCE MONITORING INPUT TO MAINTENANCE ACTIVITIES

By effectively monitoring the performance of fossil units and evaluating the data, it is possible to make reasonable predictions on the amount of performance deterioration in various turbine sections and the likely causes. By using this information to evaluate the economic impact of reliability, fuel cost and capacity, it is practical to optimize:

- The selection of the next unit for a maintenance outage

- Turbine section most in need of maintenance
- Assessment of maintenance needs in a particular turbine section
- The ordering of spare parts in time for maintenance outages
- Future outage scheduling

SUMMARY

Over the next few years, becoming the "low-cost" producer will be increasingly important. Power plant owners can make a significant contribution toward achieving this goal by implementing a well-organized performance monitoring program which will reduce fuel costs and facilitate cost-effective maintenance.

This paper has presented the common techniques used for performance monitoring of fossil steam turbines, including methods for periodic acquisition, evaluation and interpretation of performance data, as well as inspection of the turbine steam path. These features of a monitoring program are essential in order to achieve and maintain the highest level of thermal performance of a turbine-generator unit.

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LIST OF FIGURES

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