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Routine Performance Test Guidelines for Steam Turbines

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REPORT SUMMARY

With the rising cost of fuel and the strong possibility of CO_2 emissions regulations and limitations in the near future, utilities and power generation companies are focusing on power plant heat rate and performance. Improvements in heat rate, which lower fuel costs and decrease emissions, can make a difference in the financial health of a power plant, a power company, and the power industry as a whole. A set of 10 routine test guidelines was developed in 2009. Using the same methodology, an additional set of nine routine test guidelines was developed in 2010 for the periodic performance testing of power plant components and systems. This report contains two of those new test guidelines that relate to steam turbines.

Background

Good plant performance programs include testing for determining the health of its components and systems, troubleshooting problems, and optimizing performance. However, due to both cost and staff reductions, testing in power plants has become less frequent despite the importance of optimizing plant heat rate and performance in an era of rising costs and looming CO_2 emission regulations. ASME Performance Test Codes (PTCs) provide procedures for the rigorous tests typically used for acceptance testing of new equipment, but such testing is conducted very infrequently because of its very high cost. In order to provide its members and the industry as a whole with another tool to improve plant performance, the Electric Power Research Institute (EPRI) undertook the development of routine test guidelines, providing less expensive tests that produce results with more uncertainty than the PTCs tests but that can be used more frequently.

Objective

- To provide a set of routine test guidelines for the periodic performance testing of power plant steam turbines

Approach

In cooperation with interested EPRI members, the project team developed a list of routine tests of plant performance for which guidelines have been developed over a two-year period and defined a standard outline for test guidelines. As the first part of a plan to produce a full set of 15–20 guidelines over two-year period, in 2009 the team developed routine test guidelines for 10 separate actions or tests based on industry experience and best practices. In this second year of this effort, the team developed draft routine test guidelines for another nine different separate actions or tests, with two focused solely on steam turbines. As in 2009 a large group of utility engineers and industry experts from EPRI members reviewed these drafts and provided recommendations for the fine tuning needed to maximize their usefulness.

Results

These guidelines were developed to permit reliable testing of steam turbines that can produce repeatable results. These routine tests can be conducted without major financial or time investments. They are designed to be conducted with a minimal number of people and to produce results that can be used for trending, analyzing, troubleshooting, and optimizing the performance of individual pieces of power plant equipment. Power plant personnel can use the guidelines to conduct tests using common test instruments to generate the primary data with process instruments meeting the remainder of the data requirements.

The procedures in this document are designed for the following purposes:

- Long-term trending of key performance parameters
- Identifying problems
- Troubleshooting component or system problems
- Optimizing component or system operation and performance

It should be noted that these guidelines are not intended for use in establishing baseline performance and boundary conditions for retrofit projects or for evaluating contract performance guarantees.

EPRI Perspective

Conducting routine performance tests is an important component of a good plant performance program. The information contained in this report represents a significant collection of information and instructions, including techniques and good practices, related to conducting routine performance testing of power plant steam turbines.

Through the use of these guidelines, EPRI members should be able to conduct routine tests more frequently, improve the results of those tests, and ultimately improve component performance and unit heat rate.

Keywords

Heat rate
HP-IP interstage leakage
Performance test
Steam turbines
Thermal efficiency

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1
INTRODUCTION AND OVERVIEW

1.1 Background

With the rising cost of fuel and the strong possibility of CO_2 emissions regulations and limitations in the near future, utilities and power generation companies are focusing on power plant heat rate and performance. After deregulation drove cost cutting measures, the recent uncertain financial markets are providing further impetus for power plant owners and operators to focus on optimizing their costs. Since the cost of fuel is 60-80% of the overall cost of producing electricity, improvements in heat rate, which decrease emissions in parallel, can make a difference in the financial health of a power plant, a power company, and the power industry.

Due to both cost and staff reductions, testing in power plants has become less frequent. ASME Performance Test Codes (PTCs) provide procedures for rigorous tests typically used for acceptance testing of new equipment. Because of the costs involved in those tests, they are conducted very infrequently.

Good plant performance programs include testing for determining the health of its components and systems, for troubleshooting problems, and for optimizing performance. EPRI undertook the development of these routine test guidelines to provide their members and the industry another tool to improve plant performance.

1.2 Purpose

The purpose of this report is to provide a set routine test guidelines for the periodic performance testing of power plant steam turbines. This report describes the common bases and similarities of the accompanying test guidelines. Current ASME PTCs provide absolute test results with minimal uncertainty, but at a very high cost. These guidelines provide for tests with greater amounts of uncertainty in their results, but as a trade-off can be used on a regular frequency, since the cost of testing would be greatly reduced.

1.3 Key Definitions and Glossary of Terms

1.3.1 Key Definitions

System, component, or test specific terms are defined within guideline for that specific test.

Test Guideline– the outline of a method to determine the relative performance of a component or system

Routine Performance Test – an action that may be employed regularly, without great cost or large labor requirements, to determine the relative performance of a power plant component or system

Test Run – one complete set of data collected as part of a test

Test – a series of test runs sufficient to describe the performance of a system or component

Optimization – the action(s) to identify the settings to attain the operating point where a system achieves its maximum effectiveness

Calibration – the actions to determine or adjust, by comparison to a standard, the relationship of the output of an instrument to a known value

Cycle Alignment – setting of valves and flow paths to ensure the fluid and steam in the steam power cycle is routed in the intended manner

Measurement Uncertainty – the estimated error of a measurement; it defines a band in which the true value probably lies

1.3.2 Glossary of Terms

Performance Test Code – An ASME standard that provides a detailed procedure for the conduct of precision tests providing results with minimal uncertainty. These codes may be referenced in contracts other legal documents.

Feedwater Heater – a shell and tube heat exchanger that receives extraction steam drawn from the steam turbine to increase the temperature of the feedwater in advance of the feedwater entering the boiler.

Steam Turbine – a mechanical device consisting of rotating and stationary vanes that extracts energy from steam and through an attachment to an electrical generator converts that now rotational energy into electrical energy.

1.4 Acronyms

ASME – American Society of Mechanical Engineers

EPRI – Electric Power Research Institute

PTC – Performance Test Code

RTD – Resistance Temperature Detector

1.5 Unit Conversions

US customary engineering units were used in these guidelines. Please use the following table for conversion to Metric units.

US Customary Units		Metric Units
1 foot	=	0.3048 meter
1 inch	=	2.54 centimeters
1^{o}F	=	0.556^{o}C
1 pound mass (lbm)	=	0.454 kilogram (kg)
1 pound per square inch (psi)	=	6.895 kpa
1 pound per cubic foot	=	1.602 kg/m^3
1 British thermal unit (Btu) / lbm	=	2.326 joule/kilogram (J/kg)

2 DEVELOPMENT PROCESS AND DESCRIPTION OF GUIDELINES

2.1 Overview of the Guideline Development Process

The following steps outline the process used to develop the routine test guidelines that accompany this report.

- Testing Needs Identified by EPRI Members
- Develop a List of Components and Systems that should be Tested Routinely
- Develop a Standard Outline for All Routine Test Guidelines
- Write up Draft Guidelines
- Forward the Drafts to Interested EPRI Members and Experts for Review
- Incorporate the Recommendations Received into the Guidelines
- Write this Report, Attaching the Completed Guidelines
- Edit and Publish the Report

The same process was employed last year to develop and publish ten routine test guidelines as the first part of this set of routine plant performance testing guidelines.

2.2 Outline for These Routine Test Guidelines

The following outline was used for all routine test guidelines developed as part of this effort.

1. Purpose

2. Applicability

3. Data Requirements
    - Primary
    - Secondary

4. Test Pre-requisites
    - Instrument Installation
    - Instrument Calibration
    - Stability
    - Cycle Alignment / Operation
5. Test Methodology
    - Data Collection Actions
    - Documentation
6. Determination of Results
    - Data Reduction
    - Methodology and Equations
7. Interpretation of Results
8. Post Test Actions
9. Appendices
    - Definition of Terms
    - References and Sources
    - Options to Reduce Uncertainty
    - Options to Expedite Results

2.3 Information Applicable to These Guidelines

These test guidelines were developed to permit reliable testing of power plant steam turbines producing repeatable results. These routine tests can be conducted without major financial or time investments. They are designed to be conducted with a minimal number of people and produce results that may be used for trending, analyzing, troubleshooting, and optimizing the performance of power plant steam turbines.

These guidelines were written to permit power plant personnel to conduct tests utilizing common test instruments for primary data and process instruments for the remainder of the data requirements.

The following paragraphs summarize the information that is generic or applicable to all the attached guidelines.

2.3.1 Calibration

Some assurance of reliable measurements is necessary to ensure meaningful results. The portable test instruments should have been calibrated at some point in their life. More recent calibration improves the accuracy of the results, but is not necessary. Upon receipt of the test data the test engineer should conduct a reasonability check to ensure the values are within an expected range. He or she may substitute data from a backup source, e.g. the process computer, if a primary value is suspect. Pre and post test calibration of the process data source(s) are not required.

2.3.2 Data Requirements

The data for these routine tests will be acquired from process and test instrumentation. To simplify the tests, these test guidelines strive to use most of the data from process instruments and only the most crucial, key inputs from test instruments. Duplicate sources of information should be used routinely:

- As a back up in case of suspect information, and
- For future follow-up to ensure the process parameters, including those sometimes used for unit control, provide reasonable indications of reality.

Primary data have been identified as those with the largest effect on outcome of the results or have a history of being difficult to measure. A good example of a primary measurement is that of steam generator exit gas temperature. That temperature has a large effect on boiler efficiency and unit heat rate. Due to the volume of flue gas flow, its potential stratification, and the physical size of the ductwork, the measurement is subject to large uncertainties. Therefore the placement and number of instruments play a significant role in the ability to determine the true temperature.

When multiple sources exist from which to collect a specific piece of operating or performance data, the test engineer needs to designate one as primary and others as back-up. While the primary source usually provides the data used in the calculations and receives the lion’s share of attention, those duplicate, back-up data sources are useful as described above.

Specific instrument accuracies and other similar specifications are not stipulated in these guidelines. The use of instruments with high levels of accuracy and a narrow band of repeatability will provide results with less uncertainty but come with a higher cost. That trade-off is the jurisdiction of the test engineer, based on his or her needs and testing budget.

2.3.3 Trending of Results

One of the purposes of testing in accordance with these guidelines is to provide a historical trend of unit and equipment performance. To make the trend and accompanying analyses meaningful, conduct the tests and analyze the results via standard methodologies. Consistent methods will ensure results that are comparable, independent of the time between test runs. Certain pieces of data should be corrected to reference conditions. The reference conditions are those stated in the manufacturer’s contract, design documents, and turbine-generator vendor’s thermal kit. The thermal kits typically contain the heat rate and output correction curves for operation at off-design conditions. If necessary, correction factors may also be developed thermal performance evaluation models.

The results of these tests may be plotted against time on a graph containing historical data. The trends can then be used to determine the rate of change and expected performance in the future.

The uncertainty of the results may also be plotted as an error bar on the trend plot to aid the analyses and to avoid concern with less than statistically significant variations.

2.3.4 Testing Frequency

Recommended test frequencies were not provided. Since these guidelines were developed to permit the conduct of routine performance tests without major time, money, or personnel commitments, the test frequency may be optimized by the power generating company to fit best into their schedule and needs. For example, tests may be conducted immediately before and after a planned outage where work will be performed on a specific component. Another example is the application of the test results as the basis for a performance monitoring program, where testing is done regularly to ensure the input stream to the trend plots continues. The frequency of conducting these tests is dependent upon the needs and resources of each power generating company's performance program.

2.3.5 Measurement Uncertainty

Measurement uncertainty provides the range in which the true value probably lies. Measurement uncertainty is not a measured value, but instead determined analytically, based on process stability, test methodology, and instrumentation characteristics. The numerical value of measurement uncertainty is not a tolerance and should not be applied as such. The true value may just as likely lie below the tested value as above it (typically by an amount less than or equal to the measurement uncertainty).

To provide the test engineer an indication of test quality, the overall measurement uncertainty can be calculated for each test run. While no expected uncertainty levels are provided for these routine performance test guidelines, by comparing the results of pre and post test uncertainty analyses, insight can be gained on what portions of the test made the largest contribution to overall uncertainty. The test engineer will then have the information to evaluate enhancements to the test, e.g. instrument upgrades, data collection frequency, instrument redundancy. Each specific guideline contains recommendations to reduce the uncertainty of the results and improve the quality of that specific test.

The overall uncertainty contains the contributions of both the instrument biases and process fluctuations. The details of the method to determine this uncertainty value are contained in ASME PTC 19.1.

2.3.6 General References

Routine Performance Test Guidelines. EPRI, Palo Alto, CA, 2009, 1019004.

Performance Test Code 19.1, Test Uncertainty, American Society of Mechanical Engineers, 2005, New York.

Performance Test Code PM, Performance Monitoring Guidelines for Power Plants, American Society of Mechanical Engineers, 2010, New York.

Heat Rate Improvement Reference Manual: Training Guidelines. EPRI, Palo Alto, CA, 1999, TM-114073.

Turbine Cycle Heat Rate Monitoring: Technology and Application. EPRI, Palo Alto, CA, 2006, 1012220.

Heat Rate Improvement Reference Manual. EPRI, Palo Alto, CA, 1998, TR-109546.

Heat Rate Improvement Guidelines for Existing Fossil Plants. EPRI, Palo Alto, CA, 1986, CS-4554.

3
HP-IP INTERSTAGE LEAKAGE, LOAD VARIATION METHOD

HP to IP Packing Leakoff Periodic Test Guideline (load variation /slope method)

1. Purpose: To determine the leakage flow rate from the HP turbine to the IP turbine.

2. Applicability: Combined HP and IP Steam Turbines in fossil fuel power stations.

3. Data Requirements

   - Primary
     - Main steam temperature
     - Main steam pressure
     - HP turbine first stage shell pressure
     - IP turbine inlet pressure (hot reheat)
     - IP turbine inlet temperature (hot reheat)
     - IP turbine exhaust pressure
     - IP turbine exhaust temperature

   - Secondary
     - HP turbine exhaust pressure (cold reheat)
     - HP turbine exhaust temperature (cold reheat)
     - HP turbine first stage steam temperature
     - HP turbine metal temperatures
     - Barometric / local atmospheric pressure
     - Gross generation
     - Main steam or final feedwater flow rate
     - Date and time of test

4. Test Pre-requisites

- Instrument Installation

  The measurements of certain temperatures and pressure are crucial to the determination of IP turbine section efficiency and the leakage between the HP and IP turbines. Following the following recommendations for each will reduce uncertainty and provide meaningful and trendable results.

  - Pressure Measurements

    When measuring steam pressure, a column of liquid (water) will form in the sensor tubing outside the process, above the instrument. The pressure applied by the height of this water leg must be accounted for to determine the process absolute pressure, which is used to determine the steam's thermodynamic properties at that point.

    To minimize the possible errors contributed by water legs:

    – Install the pressure gages to minimize the length of sensor tubing between the process and the instrument.

    – Ensure the water leg has been blown down well in advance of the test to ensure that no air or bubbles exist in the sensor tubing and to ensure the water leg is completely re-established prior to recording data

    – Measure the difference in elevation between the centerline of the process connection and the instrument; and

    – Consistently and correctly apply the water leg correction to all steam pressure measurements i.e., subtract the pressure equivalent of the water leg from the measured pressure. (In practice, since all positive pressure instruments should be placed at or below the centerline of the process, the water leg is applying additional pressure to the instrument causing a falsely high reading.)

  - Temperature Measurements

    Thermocouples or RTDs (Resistance Temperature Device) should be used in thermowells. If the reading is suspect, the device should be removed from its well, the well cleaned, and the device re-inserted to a depth ensuring contact with the bottom of the well. All thermowells should be immersed to a depth of ¼-½ of the diameter of the process pipe.

  - Instrument Calibration

    The portable test instruments should have been calibrated. More recent calibration improves the accuracy of the results, but is not necessary. Upon receipt of the test data the test engineer should conduct a reasonability check to ensure the values are within an expected range. He or she may substitute data from a backup source, e.g., the process computer, if a primary value is suspect. Calibration of the process data source(s) is not required.

- Stability

  These tests will provide results with less uncertainty if the unit is operating in a steady state condition. During transients large components in power plants can “store” energy or heat or require additional heat, causing a delay or lag in the steam conditions, which can influence the results by an unknown amount. Therefore the unit should be at steady state for a minimum of 30 minutes prior to commencing data acquisition. To ensure steady state, the following criteria will be met:

  – Unit in manual control, not AGC

  – No control valve movement

  – Gross generation changes of less than 1% / hour

  – Main steam pressure changes of less than 0.5% / hour

  – Feedwater or main steam flow changes of less than 1% / hour

  It is recommended to initiate a trend of those parameters via a plant process computer or historian prior to the test.

  A 2 hour stabilization period is recommended prior to the low load test run.

- Cycle Alignment / Operation

  Two test runs will be conducted at different operating conditions. For the most part the steam generating unit and the main turbine should be operated in a normal line-up/mode of operation during this test. Prior to testing, unit operational system alignments should be set up such that: 1) turbine inlet steam conditions are representative of normal operation or design conditions; and 2) feedwater heater extraction steam supplies operate as close to design conditions of temperature, pressure, and flow as possible. By setting up the unit to operate in this way, the effect on turbine performance by external factors and not associated with the condition of the turbine itself, will be minimized.

  Prior to commencing the test, the turbine and associated feedwater heaters should be walked down to ensure the steam and water systems are properly aligned and the alignment remains unchanged between the test runs. Vent, drain, and bypass valves should be checked to ensure they are in the proper position (e.g., no throttle steam flow is bypassing the HP turbine inlet, and all feedwater heater emergency drains are closed). Abnormal operation of the feedwater system, e.g., leaking emergency drain valves increase the total extraction flow, which can change the downstream turbine pressures and affect the reported section efficiency. If not correctable, these abnormal conditions should be identified; their effect quantified or estimated, and reported with the test results.

  The HP-IP packing blowdown valve should be checked to ensure it is not passing flow. Due to the typical inaccessibility of this valve, thermography or other remote temperature sensing methods can be employed to check this valve.

The first test run should be conducted at or near full load conditions with steam temperatures within 3 °F of expected values. Then, unit load should be reduced by at least 30%. All operating parameters should be kept at normal values for this lower unit output test run. Once this operating condition is attained the unit should be held there for 2-4 hours. After the stabilization hold time is passed, a second test run should be conducted. At the conclusion of this test run, normal operation may resume.

5. Test Procedure

- Data Collection Actions

This guideline presents one of two methods to determine the leakage from the HP to the IP turbines utilizing IP section efficiency data. In this process, the load variation or slope method, the section efficiency test will be conducted at different operating conditions, but under the same instructions provided for these tests in the previously published EPRI guideline. Refer to EPRI Report 1019004, and the guideline for Steam Turbine Section Efficiency.

The first step is always to determine the IP section efficiency under normal operating conditions. Prior to the second test run reduce unit load by 20-50% and after a 2 hour hold for stabilization, collect the second set of data for the IP turbine.

- Documentation

The data recorded should be kept in a location and format to permit future accessibility. Immediately following the test period, the complete set of data recorded should be copied and kept separate from the original.

6. Determination of Results

- Data Reduction

All measurements of each parameter recorded during the test run should be averaged. All measured pressures shall be converted to absolute values by incorporating the applicable water leg correction and adding atmospheric pressure to gage readings. Temperatures may only be adjusted for known and documented corrections based on calibration records.

- Methodology and Equations

Actual enthalpies shall be determined for the conditions at the inlet and exhaust of each turbine. An isentropic enthalpy shall be determined using the inlet entropy and the exhaust pressure. IP turbine section efficiency for each test run should be calculated with the following equation:

Eta = (hin – hout) / (hin – houts) x 100%

Where:

Eta is the section efficiency (%)

hin* is the steam enthalpy at the turbine inlet (btu/lb)
hout is the steam enthalpy at the turbine outlet (btu/lb)
houts is the isentropic enthalpy at the outlet pressure and inlet entropy (btu/lb)

*hin is hot reheat enthalpy for the IP turbine section

Then the inlet enthalpy should be changed based on an estimated leakage flow rate. Use a value in the range of 5-10% for the estimated leakage in this next calculation based on the following equation:

hinl = (hhrh + lkg * hl / 100) / (1 + lkg / 100)

Where:

hinl is the steam enthalpy at the turbine inlet accounting for leakage (btu/lb)
hhrh is the hot reheat steam enthalpy measured entering the IP turbine (btu/lb)
lkg is the estimated leakage flow compared to reheat flow in %
hl is the enthalpy of the leakage flow (btu/lb)

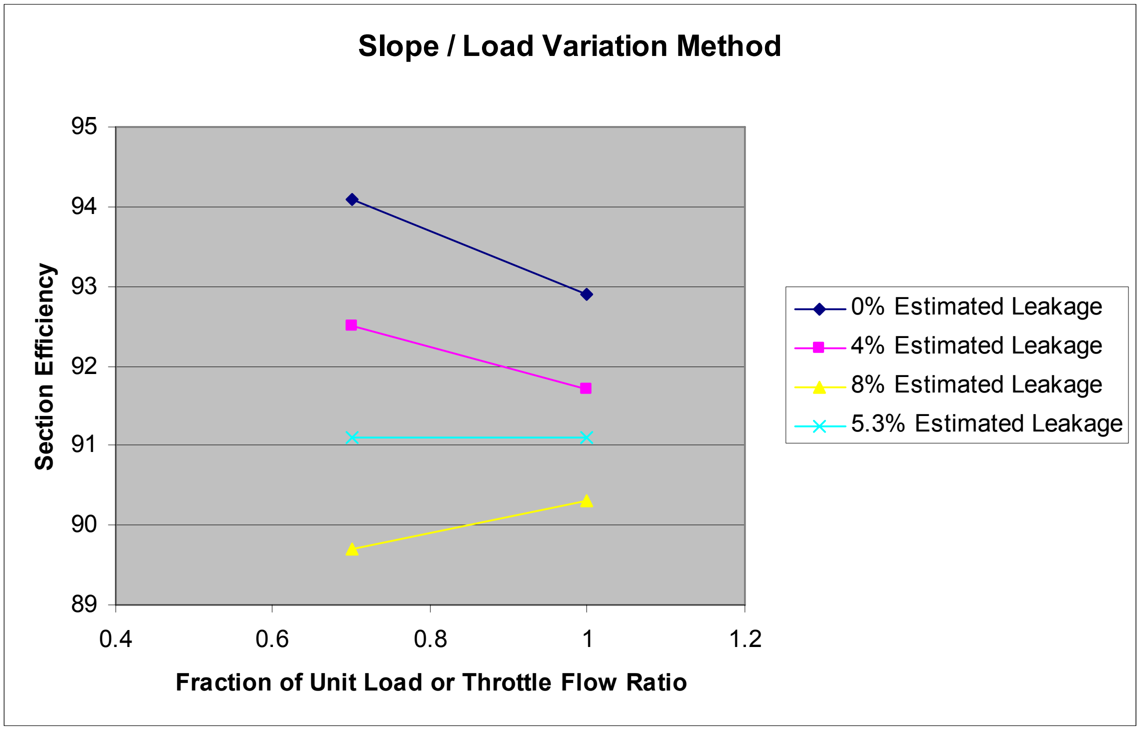
For most instances equating the leakage enthalpy to that of main steam enthalpy will not cause gross errors. For additional precision, refer to the section later in this guideline on methods to reduce the uncertainty.

Substitute the IP inlet enthalpy adjusted for leakage into the standard equation for turbine section efficiency and determine the section efficiency again. Plot the two section efficiencies on a graph as a function unit load or throttle flow ratio and connect the two points with a straight line.

Repeat these steps with the data collected during operation with the load variation. Plot these two points on the same graph and connect them with a straight line. Compare the slopes of those two lines. The goal is to identify a leakage that will produce a line with a 0.0 slope, where the IP section efficiencies at both tested points are equal.

Repeat the steps above, calculating the IP section efficiency at the two throttle flow ratios with different estimated leakages. The estimated leakage used to plot the line with a zero slope denotes the actual leakage.

The following plot contains fictitious data as an example. The results from these fictitious test runs were determined for four different estimated leakages. The estimated leakage of 5.3% resulted in a line with zero slope and indicating that is the leakage rate for this test series.



7. Interpretation of Results

Several iterations may be required to identify the estimated leakage that yields a zero slope. If the estimated leakage has been increased beyond 20% and the slope is still negative, either the turbine leakage is very large or the test results are suspect. Repeat the test to verify the data and/or validate the results.

The leakage rate should be trended over time. Between major turbine overhauls a slow degradation in seal leakage will occur due to normal wear and tear.

A sudden change in seal leakage is an indicator of a mechanical problem. Examples include:

– physically damaged seals caused by events that results in contact with shaft (a rub)

– physically damaged seals caused by solid particle erosion

– physically damaged seals caused by foreign material impingement

– a broken hold-down spring no longer keeping the seal in place

The leakage should decrease dramatically following a turbine overhaul in which seal work was performed. The magnitude of that improvement is a function of the amount of physical work done and the success of those restorations.

Other sources of leakage may include snout rings, the HP turbine inner shell, and the HP turbine horizontal joint.

8. Post Test Actions

   Test results (the HP to IP turbine leakage flow rate) should be trended over time. Causes of abrupt changes should be determined and if unexplainable, additional testing to confirm should be considered. Maintenance or inspection outage scheduling may be based on the trend of leakage rate and an estimated cost of poorer performance as the losses and the outage costs may be compared to the expected recovery and fuel savings to determine the cost-benefit of such actions.

   Records from steam path audits can be used to estimate the losses caused by increased seal clearances.

9. Appendices

   - Definition of Terms
     - Section Efficiency is the amount of energy produced by a section of a turbine compared to the maximum energy that section may have produced.
     - The throttle flow ratio is the throttle flow rate at the test conditions divided by the throttle flow rate at design conditions, typically valves wide open (VWO).
   - References and Sources
     - ASME Documents

– PTC 6S – 1988	Procedures for Routine Performance Tests of Steam Turbines
– PTC PM – 2010	Performance Monitoring Guidelines for Steam Power Plants
– PTC 19.3 – 1974	Temperature Measurement
– PTC 19.2 – 1987	Pressure Measurement

     - EPRI Documents

       – Turbine Cycle Heat Rate Monitoring: Technology and Application, EPRI Report 1012220

       – Estimating the Leakage from HP to IP Turbine Sections, Booth, J and Kautzman, D, from the 1984 Power Plant Performance Workshop Proceedings EPRI Report CS-4545SR

     - Other Documents

       – A Practical Guide to N2 Packing Testing on GE Combined HP-IP Turbines, Moore, M.S. from the 1992 Heat Rate Improvement Conference Proceedings

       – Recommended Procedures for Measuring HP-IP Turbine Leakage Flow, Haynes, C. J., et.al.

   - Options to Reduce Uncertainty

     To reduce uncertainty, one can use redundant instruments for each primary data point. Calibrating the instrument prior to the test runs assures one of reduced uncertainty, but is costly. After the test runs, calibrating only those instruments with or having indicated values outside the expect range is another good practice to improve the reliability of the results. If the post-test calibration indicates a problem, the results can be corrected or another test run conducted. Increasing the test duration and amount of data sets collected, as long as the unit's stability is maintained, will reduce the uncertainty.

The existence and height of water legs in pressure sensor tubing can be confirmed by the use of portable infra-red or thermography instruments.

The mass of the turbine is large and metal temperature changes lag behind those of steam temperature. By lengthening the hold time prior to the test run(s) conducted at lower loads, the system may be closer to equilibrium.

Conducting a third test run at a load much different than the first two, adds a third point to the each plotted line and confirms the slope.

Taking the temperature measurements on the LP turbine crossover piping instead of the IP turbine exhaust will permit more room for mixing and avoid any effects due to the high temperature of the IP turbine casing.

While the actual value of the leakage enthalpy has a very small effect on the results, one may use other ways to estimate it more accurately. The first is to locate the value on a design heat balance. Another is to plot the HP expansion on a Mollier diagram to identify the enthalpy at the first stage pressure.

Substitute throttle flow ratio for load in the graph. To do so determine throttle flow ratio for each test run. The throttle flow is the amount of steam entering the HP turbine first stage. It can be determined by measuring the feedwater or main steam flow rate and accounting for all flows leaving and entering prior to passing through the HP turbine. Depending upon the cycle configuration, flows that should be accounted for may include:

– boiler blowdown

– control valve leakages

– attemperating spray(s)

– feed pump seal leakage

– boiler circulating pump seal injection

– boiler circulating pump seal leakage

Drawing a control volume extending from the measurement point to the HP turbine may help identify the flow paths to be considered. Some of the leakages may be estimated from design documents and the turbine thermal kit.

- Options to Expedite Results

Employing a spreadsheet with steam table call functions to determine section efficiency from a set of test data, ensures consistency and reduces the time from test run to results.

The adjustment to section efficiency for estimated leakage can also be set up into a spreadsheet calculation. Some online performance monitoring systems have internal routines that continuously determine turbine section efficiencies from process data, but will not determine the adjustment.

Conducting the second test run at a load greater than the recommended 70% may still provide a reasonable estimate of the leakage flow rate, while being easier to achieve. The maximum load for the second test run should be no greater than 80% to provide meaningful results.

4

HP-IP INTERSTAGE LEAKAGE, TEMPERATURE VARIATION METHOD

HP to IP Packing Leakoff Periodic Test Guideline (temperature variation method)

1. Purpose: To determine the leakage flow rate from the HP turbine to the IP turbine.

2. Applicability: Combined HP and IP Steam Turbines in fossil fuel power stations.

3. Data Requirements

   - Primary
     - Main steam temperature
     - Main steam pressure
     - HP turbine first stage shell pressure
     - IP turbine inlet pressure (hot reheat)
     - IP turbine inlet temperature (hot reheat)
     - IP turbine exhaust pressure
     - IP turbine exhaust temperature
   - Secondary
     - HP turbine exhaust pressure (cold reheat)
     - HP turbine exhaust temperature (cold reheat)
     - HP turbine first stage steam temperature
     - HP turbine metal temperatures
     - Barometric / local atmospheric pressure
     - Gross generation
     - Date and time of test

4. Test Pre-requisites

   - Instrument Installation

The measurements of certain temperatures and pressure are crucial to the determination of IP turbine section efficiency and the leakage between the HP and IP turbines. Following the following recommendations for each will reduce uncertainty and provide meaningful and trendable results.

- Pressure Measurements

  When measuring steam pressure, a column of liquid (water) will form in the sensor tubing outside the process, above the instrument. The pressure applied by the height of this water leg must be accounted for to determine the process absolute pressure, which is used to determine the steam's thermodynamic properties at that point.

  To minimize the possible errors contributed by water legs:

  – Install the pressure gages to minimize the length of sensor tubing between the process and the instrument.

  – Ensure the water leg has been blown down well in advance of the test to ensure that no air or bubbles exist in the sensor tubing and to ensure the water leg is completely re-established prior to recording data

  – Measure the difference in elevation between the centerline of the process connection and the instrument; and

  – Consistently and correctly apply the water leg correction to all steam pressure measurements i.e., subtract the pressure equivalent of the water leg from the measured pressure. (In practice, since all positive pressure instruments should be placed at or below the centerline of the process, the water leg is applying additional pressure to the instrument causing a falsely high reading.)

- Temperature Measurements

  Thermocouples or RTDs (Resistance Temperature Device) should be used in thermowells. If the reading is suspect, the device should be removed from its well, the well cleaned, and the device re-inserted to a depth ensuring contact with the bottom of the well. All thermowells should be immersed to a depth of ¼-½ of the diameter of the process pipe.

- Instrument Calibration

  The portable test instruments should have been calibrated. More recent calibration improves the accuracy of the results, but is not necessary. Upon receipt of the test data the test engineer should conduct a reasonability check to ensure the values are within an expected range. He or she may substitute data from a backup source, e.g., the process computer, if a primary value is suspect. Calibration of the process data source(s) is not required.

- Stability

  These tests will provide results with less uncertainty if the unit is operating in a steady state condition. During transients large components in power plants can "store" energy or heat or require additional heat, causing a delay or lag in the steam conditions, which can influence the results by an unknown amount. Therefore the unit should be at steady state for a minimum of 30 minutes prior to commencing initial data acquisition. To ensure steady state, the following criteria will be met:

– unit in manual control, not AGC

– no control valve movement

– gross generation changes of less than 1% / hour

– main steam pressure changes of less than 0.5% / hour

– feedwater or main steam flow changes of less than 1% / hour

It is recommended to initiate a trend of those parameters via a plant process computer or historian prior to the test.

A one hour stabilization period is recommended prior to the temperature drop test run.

- Cycle Alignment / Operation

  Two test runs will be conducted at different operating conditions. For the most part the steam generating unit and the main turbine should be operated in a normal line-up/mode of operation during this test. Prior to testing, unit operational system alignments should be set up such that: 1) turbine inlet steam conditions are representative of normal operation or design conditions; and 2) feedwater heater extraction steam supplies operate as close to design conditions of temperature, pressure, and flow as possible. By setting up the unit to operate in this way, the effect on turbine performance by external factors and not associated with the condition of the turbine itself, will be minimized.

  Prior to commencing the test, the turbine and associated feedwater heaters should be walked down to ensure the steam and water systems are properly aligned and the alignment remains unchanged between the test runs. Vent, drain, and bypass valves should be checked to ensure they are in the proper position (e.g., no throttle steam flow is bypassing the HP turbine inlet, and all feedwater heater emergency drains are closed). Abnormal operation of the feedwater system, e.g., leaking emergency drain valves increase the total extraction flow, which can change the downstream turbine pressures and affect the reported section efficiency. If not correctable, these abnormal conditions should be identified; their effect quantified or estimated, and reported with the test results.

  The HP-IP packing blowdown valve should be checked to ensure it is not passing flow. Due to the typical inaccessibility of this valve, thermography or other remote temperature sensing methods can be employed to check this valve.

  The first test run should be conducted at or near full load conditions with steam temperatures within 3°F of expected values. Then, main steam temperature should be reduced* by about 50°F. Once this operating condition is attained the unit should be held there for at least one hour. After the stabilization hold time is passed, a second test run should be conducted. At the conclusion of this test run, operating parameters should be returned to normal.

* potential methods include increasing attemperation spray flow rate, reducing burner tilts, temporarily suspending soot-blowing of the superheater elements.

5. Test Procedure

- Data Collection Actions

  This guideline presents one of two methods to determine the leakage from the HP to the IP turbines utilizing IP section efficiency data. In this process, the temperature variation method, the section efficiency test will be conducted at different operating conditions, but under the same instructions provided for these tests in the previously published EPRI guideline. Refer to EPRI Report 1019004, and the guideline for Steam Turbine Section Efficiency.

  The first step is always to determine the IP section efficiency under normal operating conditions. Prior to the second test run reduce main steam temperature by approximately 50°F and after a one hour or longer hold for stabilization, collect the second set of data for the IP turbine.

- Documentation

  The data recorded should be kept in a location and format to permit future accessibility. Immediately following the test period, the complete set of data recorded should be copied and kept separate from the original.

6. Determination of Results

- Data Reduction

  All measurements of each parameter recorded during the test run should be averaged. All measured pressures shall be converted to absolute values by incorporating the applicable water leg correction and adding atmospheric pressure to gage readings. Temperatures may only be adjusted for known and documented corrections based on calibration records.

- Methodology and Equations

  Actual enthalpies shall be determined for the conditions at the inlet and exhaust of each turbine. An isentropic enthalpy shall be determined using the inlet entropy and the exhaust pressure. IP turbine section efficiency for each test run should be calculated with the following equation:

  Eta = (hin – hout) / (hin – houts) x 100%

  Where:

  Eta is the section efficiency (%)

hin* is the steam enthalpy at the turbine inlet (btu/lb)
hout is the steam enthalpy at the turbine outlet (btu/lb)
houts is the isentropic enthalpy at the outlet pressure and inlet entropy (btu/lb)

*hin is hot reheat enthalpy for the IP turbine section

Then the inlet enthalpy should be changed based on an estimated leakage flow rate. Use a value in the range of 5-10% for the estimated leakage in this next calculation based on the following equation:

hinl = (hhrh + lkg * hl / 100) / (1 + lkg / 100)

Where:

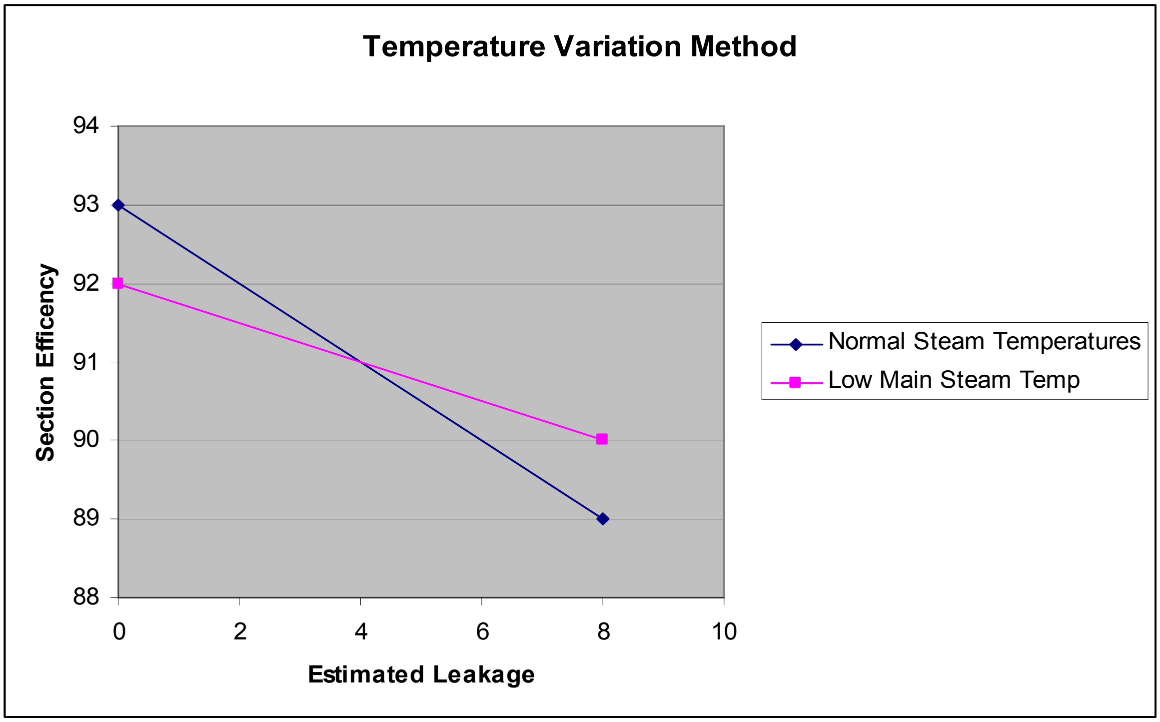
hinl is the steam enthalpy at the turbine inlet accounting for leakage (btu/lb)
hhrh is the hot reheat steam enthalpy measured entering the IP turbine (btu/lb)
lkg is the estimated leakage flow compared to reheat flow in %
hl is the enthalpy of the leakage flow (btu/lb)

For most instances equating the leakage enthalpy to that of main steam enthalpy will not cause gross errors. For additional precision, refer to the section later in this guideline on methods to reduce the uncertainty.

Substitute the IP inlet enthalpy adjusted for leakage into the standard equation for turbine section efficiency and determine the section efficiency again. Plot the two section efficiencies on a graph as a function of leakage and connect the two points with a straight line.

Repeat these steps with the data collected during operation with the temperature variation. Plot these two points on the same graph and connect them with a straight line.

The intersection of the two lines denotes the actual leakage. The following plot contains fictitious data as an example. The results from these fictitious test runs were adjusted for an estimated 8% leakage. These two lines intersect indicating a leakage of 4%.



7. Interpretation of Results

If at first the lines do not intersect, re-calculate the results at a greater estimated leakage. If they do not intersect within 20% leakage, either the turbine leakage is very large or the test results are suspect. Repeat the test to verify the data and/or validate the results.

The leakage rate should be trended over time. Between major turbine overhauls a slow degradation in seal leakage will occur due to normal wear and tear.

A sudden change in seal leakage is an indicator of a mechanical problem. Examples include:

– physically damaged seals caused by events that results in contact with shaft (a rub)

– physically damaged seals caused by solid particle erosion

– physically damaged seals caused by foreign material impingement

– a broken hold-down spring no longer keeping the seal in place

The leakage should decrease dramatically following a turbine overhaul in which seal work was performed. The magnitude of that improvement is a function of the amount of physical work done and the success of those restorations.

Other sources of leakage may include snout rings, the HP turbine inner shell, and the HP turbine horizontal joint.

8. Post Test Actions

   Test results (the HP to IP turbine leakage flow rate) should be trended over time. Causes of abrupt changes should be determined and if unexplainable, additional testing to confirm should be considered. Maintenance or inspection outage scheduling may be based on the trend of leakage rate and an estimated cost of poorer performance as the losses and the outage costs may be compared to the expected recovery and fuel savings to determine the cost-benefit of such actions.

   Records from steam path audits can be used to estimate the losses caused by increased seal clearances.

9. Appendices

   - Definition of Terms
     - Section Efficiency is the amount of energy produced by a section of a turbine compared to the maximum energy that section may have produced.

   - References and Sources
     - ASME Documents
       - – PTC 6S – 1988 Procedures for Routine Performance Tests of Steam Turbines
       - – PTC PM – 2010 Performance Monitoring Guidelines for Steam Power Plants
       - – PTC 19.3 – 1974 Temperature Measurement
       - – PTC 19.2 – 1987 Pressure Measurement
     - EPRI Documents
       - – Turbine Cycle Heat Rate Monitoring: Technology and Application, EPRI Report 1012220
       - – Estimating the Leakage from HP to IP Turbine Sections, Booth, J and Kautzman, D, from the 1984 Power Plant Performance Workshop Proceedings EPRI Report CS-4545SR
     - Other Documents
       - – A Practical Guide to N2 Packing Testing on GE Combined HP-IP Turbines, Moore, M.S. from the 1992 Heat Rate Improvement Conference Proceedings
       - – Recommended Procedures for Measuring HP-IP Turbine Leakage Flow, Haynes, C J, et.al.

   - Options to Reduce Uncertainty

     To reduce uncertainty, one can use redundant instruments for each primary data point. Calibrating the instrument prior to the test runs assures one of reduced uncertainty, but is costly. After the test runs, calibrating only those instruments with or having indicated values outside the expect range is another good practice to improve the reliability of the results. If the post-test calibration indicates a problem, the results can be corrected or another test run conducted. Increasing the test duration and amount of data sets collected, as long as the unit's stability is maintained, will reduce the uncertainty.

The existence and height of water legs in pressure sensor tubing can be confirmed by the use of portable infra-red or thermography instruments.

Conduct additional test runs at additional main steam temperatures. Each additional steam temperature will provide another line on the plot. If multiple lines intersect at the same point, the confidence in the results is increased.

Conduct additional test run(s) with normal main steam temperatures, but with lower than normal hot reheat temperature(s).

The mass of the turbine is large and metal temperature changes lag behind those of steam temperature. By lengthening the hold time prior to the test run(s) conducted at non-normal steam temperatures, the system may be closer to equilibrium.

While the actual value of the leakage enthalpy has a very small effect on the results, one may use other ways to estimate it more accurately. The first is to locate the value on a design heat balance. Another is to plot the HP expansion on a Mollier diagram to identify the enthalpy at the first stage pressure.

Taking the temperature measurements on the LP turbine crossover piping instead of the IP turbine exhaust will permit more room for mixing and avoid any effects due to the high temperature of the IP turbine casing.

- Options to Expedite Results

  Employing a spreadsheet with steam table call functions to determine section efficiency from a set of test data, ensures consistency and reduces the time from test run to results. The adjustment to section efficiency for estimated leakage can also be set up into a spreadsheet calculation. Some online performance monitoring systems have internal routines that continuously determine turbine section efficiencies from process data, but will not determine the adjustment.

  Conducting the second test run at a reduced temperature variation less than the recommended 50°F below normal operating temperature may still provide a reasonable estimate of the leakage flow rate, while being easier to achieve. The temperature variation should be no less than 30°F to provide meaningful results.

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