STEAM TURBINE AUDIT STUDY

Purpose of the Audit

The purpose of the steam path audit was to assess the thermal performance of the steam turbine-generator. The results of this audit identified specific problem areas and quantified the impact of the problems in order to assist the OWNER in making decisions whether to repair or replace steam path components.

STEAG studied the turbine heat balance to characterize the unit's performance in its new-and-clean condition. Steam path audit data were taken during the outage to determine the condition of the steam path.

1.1 Description of the Audit

The audit made use of the proprietary Steam Turbine Performance Evaluation (eSTPE) computer software that Encotech developed for use by power producers. The eSTPE program accepts the measured data collected during the on-site investigation and calculates the resulting power loss and heat rate degradation for each loss category, independent of other losses, at each turbine stage. The results of solid particle erosion, foreign object damage, and deposits are combined, however, to best represent the conditions of the unit at the time of the audit.

The basic approach of the audit is to examine the entire turbine steam path in detail and compare the as-found condition with the new-and-clean condition of the machine.

The new-and-clean condition of the unit was modeled in eSTPE using the heat balance shown in section four. This model was used for comparison purposes since it represents the turbine as it is expected to operate. This model provides a representative condition to be used as a basis for comparisons.

eSTPE compares as-found data collected during the audit with the new-and-clean condition characterized in the software “Design” section. The Design portion of the eSTPE computer program calculates the turbine geometric properties, the thermodynamic and fluid dynamic conditions at each stage, efficiency margins, and other operation and design dependent properties using the turbine geometry and the heat balance. Although complete restoration to the new-and-clean condition is generally not possible, it provides a fixed standard for comparisons.

eSTPE evaluates losses on a stage-by-stage basis but recognizes that some losses in early stages can be recovered down stream. Two important considerations are: first, the regain to steam flowing to downstream stages due to increases in downstream available energy and second, the reduced heat input required by the boiler resulting from losses that occur above a reheat point. The analysis used in eSTPE accounts for both of these effects when calculating stage losses.

1.2 Areas Addressed in the Audit

The specific areas of concern addressed by the audit are:

1) Leakages:
- past stationary stage blading
- past rotating stage blading
- past shaft end packings where rotors emerge from casings
- across poorly fitting joints
- other miscellaneous leakages

2) Surface finish degradation:
- deposits

3) Flow blockages from:
- deposits
- foreign objects
- mechanical damage

4) Flow path modification from:
- solid particle erosion

- corrosion
- solid particle erosion
- mechanical damage

- water droplet erosion
- mechanical damage

1.3 eSTPE Report Format

The eSTPE Program generates loss reports for individual stages, individual casings, and the entire turbine. The Turbine and Casing Loss Summary Reports contained in section one outline the losses calculated in the individual loss categories, such as tip spill strips, and provide totals of the heat rate and power losses for each loss category and each casing. The Loss Category Turbine Loss reports contained in section five compile total casing losses for one type of loss, for example Interstage Packing Leakages occurring in the HP turbine casing. The Loss Category Casing Loss reports contained in section five provide the calculated change in power loss and change in heat rate for each stage in the casing for each loss area.

1.4 A Note on Power Loss and Heat Rate

The Change In Power Loss is the calculated decrease in gross output power, including generator and mechanical losses, for the stage or casing noted on the report. The Change in Heat Rate is the degradation of the gross turbine heat rate for the unit.

The Total Change in Power Loss is a summation of the stage power losses from individual loss categories. The Total Change In Heat Rate is not, however, a summation of the heat rate changes from individual categories. The change in heat rate is a function of the power loss. This function is non-linear with respect to power and, therefore, cannot be summed in a linear manner. The Change in Heat Rate is the degradation in the gross turbine heat rate resulting from the specific power loss and change in boiler duty, if any.

1.5 Leakages

Leakages are steam flows that bypass either stationary or rotating turbine components. Leakage flows include flows through leakage control devices such as interstage packings or end packings (labyrinth-type packings), and tip spill strips as well as other miscellaneous leakages past expansion joints, stationary blade carrier seals, or leakages along the horizontal joint.

1.6 Shaft Packings

Labyrinth-type packings control leakage between stationary and rotating parts in the machine. These packings include:

- Interstage Packings located at the inside diameter of the stationary blading and root spill strips located near the root of the rotating blading,
- End Packings located where rotors emerge from casings, and
- Tip Spill Strips located at the tips of the rotating blades.

To calculate packing losses, the auditor determines the difference in leakage area calculated from the original design clearances. Wear is determined by subtracting the height of the worn tooth from that of the design tooth. The wear is then added to the design clearance to estimate the clearance in the running condition. To estimate clearances at the top and bottom of the rotor, the auditor measures tooth heights at the horizontal joint and at the top and bottom of the packing. The auditor then makes four additional tooth height measurements at locations around the casing circumference: the upper left, the upper right, the lower left, and the lower right. eSTPE calculates an average clearance and leakage area from these measurements and compares it to the design value.

The eSTPE program also applies a tooth condition to all packings. A “rounded” set of teeth will exhibit a greater flow passing capability than a sharp set of teeth. Rubbing of a steam packing causes the packing tooth to “mushroom” out at the tip, causing a rounded tooth tip.

Tooth rounding may also be caused by solid particle erosion of the tip of the packing tooth. Sharpening any packing tooth that is rounded will result in a performance benefit by reducing the flow through the packing.

After determining the change in leakage area and tooth condition, eSTPE uses Martin's flow formula to calculate the change in leakage flow from design. Important inputs to this calculation are the pressures on each side of the packing and the upstream specific volume. The auditor can determine these parameters readily for end packings, from the heat balance, but since these parameters are functions of the reaction at the root and tip of each stage more information is needed to determine flows past stationary and rotating blading. For this purpose, eSTPE uses the Design section of the program that calculates root, pitch, and tip reactions of each stage. Other important inputs to the calculation of packing flows are the number of teeth currently in place, compared with the expected or design value, and the condition of those teeth. Losing teeth in service and increasing the flow coefficient due to packing rubbing can both increase packing leakage.

The packing GAP is the distance between the packing land (usually on the rotor or rotating blade cover) and the base of the measured tooth. The gap (GAP) is calculated from the left and right measured clearances and the left and right measured tooth heights.

$$GAP = \frac{1}{2}\left[(C_R + t_R) + (C_L + t_L)\right] \qquad (1)$$

The average measured clearance (C_{ave}) is calculated from the average packing GAP and the eight measured tooth heights.

$$C_{ave} = \frac{1}{8}\sum_{i=1}^{8} GAP_{ave} - t_i \qquad (2)$$

The Horizontal Gap Variance (HGV) is calculated as one half the difference between the left and the right GAP.

$$HGV = \frac{GAP_L - GAP_R}{2} \qquad (3)$$

Where:
HGV = Horizontal Gap Variance
GAP = radial distance between packing land and tooth base
C_{ave} = average clearance
t = tooth height
c = clearance
L = left side of turbine while facing the generator
R = right side of turbine while facing the generator

eSTPE uses this method to calculate average clearance and the horizontal gap variance for interstage packings, end packings, and tip spill strips.

1.7 Typical Causes For Uneven Packing Wear

Some typical causes for uneven top-to-bottom or side-to-side wear patterns are:

1. rotor to casing misalignment,
2. response of the rotor to unbalance, especially when passing through critical speeds,
3. differences in temperature between the top and bottom of the turbine casing causing distortion during hot or still-warm starts and during stops, and
4. differences between the vertical thermal expansions of the casing supports and of the rotor.

1.8 Reducing Packing Wear

Maintenance actions that can reduce instances of uneven packing wear patterns include:

1. careful alignment of the stationary blade rows and inner casings,
2. careful balancing of the turbine rotor,
3. careful placement of insulation applied to the casing and to the connections of the extractions, and
4. adherence to recommended start-up procedures.

1.9 Miscellaneous leakages

eSTPE calculates miscellaneous leakages on an individual or case-by-case basis. The leakage area is calculated from leakage site geometric data input by the auditor. The auditor also determines and inputs the expected flow coefficient for the type of leakage found. The miscellaneous leakage flow is then calculated by applying the equations for flow through orifices.

1.10 Surface Finish Degradation

The method for quantifying the impact of surface finish degradation makes use of laboratory data on cascade efficiencies developed by V.T. Forster. The auditor uses a surface roughness comparator to evaluate each surface of each stationary and rotating blade row in the turbine. The surface roughness comparator uses the standard grades of emery paper Mr. Forster used in his tests. eSTPE uses “Emery Grit Size” to compare as-found surface finish to that when the machine originally went into service. It then calculates stage efficiencies for the assumed new condition (32 or 64 microinch center line average) and a modified stage efficiency for the observed existing surface finish. The modified stage efficiencies are then used to calculate a resulting power and heat rate loss for each stage.

The impact of water droplet erosion on turbine efficiency is often negligible, but is an important factor to consider when it threatens the unit’s mechanical integrity. The main change in flow path efficiency attributable to water droplet erosion is an increase in surface roughness of the leading edge of the blades in the low pressure areas where Reynolds numbers are small. Forster and others determined in laboratory tests that increased leading edge surface roughness has relatively little effect on cascade efficiency.

1.11 Increased and Decreased Flow Area

Damage to the turbine blading can cause the flow area of a stationary or rotating blade row to increase or decrease from design. Changes in flow path area are caused primarily by solid particle erosion, mechanical damage, or deposits result in increased heat rate.

1.12 Flow Path Damage

eSTPE addresses changes in cascade flow area in a section titled “Flow Path Damage”. Data are entered into the Solid Particle Erosion, Deposits, and Mechanical Damage subsections for flow path damage analysis. Each of these three sections calculates a change in area and flow coefficients from the data input into each section. The areas and coefficients from each of the three sections listed above are then combined together to calculate single area and flow coefficient change for each stationary and rotating blade row. These changes are then used to calculate an efficiency change for each damaged stage and the associated power and heat rate losses.

Changes in the cascade flow area not only affect the stage with the observed area change, but also affect interstage pressures before and after the damaged stage and the distribution of energy between the stages. The effect of area changes may cause power and heat rate losses several stages before and after the affected stage. Power loss due to change in flow, pressure, and available energy on undamaged stages appear in the casing and turbine loss summaries under the heading “Flow Change Impact”.

1.13 Solid Particle Erosion

To evaluate area changes caused by solid particle erosion, the auditor measures the geometry of the cascade and the amount of the partition trailing edge that is removed. eSTPE uses the geometry of the cascade and the trailing edge cutback to calculate a change in nozzle area and a change in the velocity diagram between the stationary and rotating components.

1.14 Mechanical Damage

Foreign objects, deposits, corrosion, and other mechanical damage to the steam path can cause an increase in flow area or a flow blockage. To determine the performance degradation caused by the damage, the auditor estimates the change in flow area for each stage. eSTPE then uses this area change information to calculate changes in the stage flow coefficients and determines the impact on adjacent stages resulting from a change in pressure ratios and stage energies.

1.15 Deposits

Deposits on the turbine steam path both increase the flow path surface roughness and may, if thick enough, decrease the flow area of the cascade. To determine the performance degradation caused by thick deposits, the auditor measures the deposit thickness and the design nozzle area to determine the change in flow area caused by the deposition. eSTPE uses the nozzle exit area and the deposit thickness information to calculate changes in cascade flow passing ability and changes in the velocity coefficient for the cascade.

1.16 Rotating Blade Cover Deposits

Solid particles that travel through the steam path are subjected to centrifugal force from the rotating elements in the turbine. Steam carries these particles though the turbine where they may impact on the stationary blading and cause solid particle erosion. As these particles lose momentum they move outward toward the tips of the rotating blading. The particles then either travel through the tip spill strip, causing spill strip erosion, or lodge underneath the rotating blade covers.

The deposits under the rotating blade covers cause a flow disturbance that affects the rotating blade velocity coefficient for a short radial portion of the rotating blade.

The auditor measures the average depth of deposits under the rotating blade covers. eSTPE uses this data along with the recorded turbine geometry to determine the impact of the deposits on turbine power and heat rate.

1.17 Increased Trailing Edge Thickness

The trailing edges of stationary blades are typically 15 to 30 mils thick by design to satisfy aerodynamic and mechanical concerns. This thickness is limited to minimize flow separation at the nozzle discharge. Partition weld repairs to correct solid particle erosion and mechanical damage often leave trailing edges thicker than design. The thickened trailing edges introduce a flow disturbance at the nozzle exit. This flow disturbance is reflected in the velocity coefficient of the steam leaving the interstage blading and causes a velocity diagram efficiency loss.

To determine the power and heat rate impacts caused by increased trailing edge thickness the auditor measures the average trailing edge thickness and the nozzle opening. eSTPE then compares the measured trailing edge thickness to the design trailing edge thickness of 20 mils.