STEAM TURBINE EFFICIENCY ENHANCEMENT SOLUTIONS FOR UTILITY POWERPLANT APPLICATIONS

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I. ABSTRACT

A continuing concern to operators of steam turbines is increasing operating costs. These costs reflect not only the rising cost of fuel and materials but also the decreased efficiency of the aging turbine fleet. Over time, damage to turbine components and increased steam leakage are the major factors resulting in lost efficiency. Steam leakage alone can account for as much as 80 percent of the efficiency losses in turbines.

Since the cost of fuel and materials is largely beyond the control of steam turbine operators, the primary mechanism for realizing savings is in the improvement of turbine efficiency.

An innovative program has been developed to appraise, evaluate, and restore steam turbine efficiency without major modifications to components. New turbine seal technology coupled with improved repair methods can enhance efficiency gains. This paper describes improved methods of analysis, evaluation, and repair now available to improve unit performance.

II. INTRODUCTION

Due to increasing operating costs, the owners and operators of steam electric generation plants work under considerable pressure to maximize the reliability, efficiency, and capacity of their plants. In this regard, the single most critical component of the steam electric generation plant is the steam turbine. Most steam turbines operate below optimum efficiency levels by as much as several percentage points due to many factors including damage, deposits, misalignment, unusual flow phenomena, and steam leakage. Additionally, reliability is frequently compromised by these factors. Sub-optimum unit performance is becoming increasingly more costly as prices for fuel and materials rise and production competition becomes tougher. Detailed evaluation of the turbine’s operating state, and practical selection of performance improvements are critical to optimum operation of the electric generation plant. Application and implementation of state-of-the-art aftermarket replacement components, along with improved operating procedures and techniques, can lead to significant improvements in reliable performance and sustained optimum efficiency and capacity.

Due in part to rising operating costs, as well as an increasingly competitive energy marketplace; steam turbine thermal performance has become an extremely important aspect of the power industry’s fleet maintenance programs. Although returning of the turbine to its maximum achievable efficiency is one primary goal of the maintenance overhaul, the industry’s trend towards an increased Mean-Time-Between-Overhaul (MTBO) demands new methods for **sustaining** high-efficiency levels over longer periods of operation. With recent development of cutting-edge technologies sustained high-efficiency has become a practical goal for turbine Operations and Maintenance teams.

A thorough understanding of actual turbine efficiency level is important, and the author emphasizes that the nucleus of a turbine maintenance program should be centered around the following inspection and repair/improvement activities:

- Accurate and regular programs of performance testing
- Regular analysis of test data for identification of trends and "events"
- Appraisal of steam path conditions and quantification of damage mechanisms
- Expert repair of components to return them to their optimum efficiency and reliability states
- Regular application of available component reliability and efficiency upgrades
- Quantifiable verification of the results of maintenance activities

Throughout the following pages, the author will identify specific areas of the turbine steam path that are critical to thermal performance and reliability, and will describe enhancements which can significantly improve both turbine reliability and efficiency.

III. PERFORMANCE EVALUATION

The value and credibility of any maintenance program aimed at heat rate improvement lies in the commitment to performing regular, accurate testing of the equipment and proper verification and interpretation of test results. A strong commitment to investing the time and money into such testing programs pays off by providing the user with intelligence which can be used to identify unit damage as well as practical improvements in maintenance and operating procedures. Several effective programs have evolved over the past decade which can be used to identify potential mechanisms affecting steam turbine performance and reliability. These programs frequently utilize advanced on-line instrumentation and data collection systems. In line with this philosophy and as a result of continuing development of programs to improve the efficiencies of steam turbines, several practical approaches to unit testing have been developed. The application of on-line systems to document and evaluate turbine performance trends is a significant factor in the current emphasis on heat rate improvement. An outline of how such a program might be used is as follows:

- Identify operating parameters which will provide meaningful information regarding trends and/or events which could affect reliability and/or efficiency.
- Define acceptable value ranges and flag points.
- Monitor specified parameters and collect data using on-line monitoring system.
- Analyze data, either with on-line Smart System, or manually, and compare against a set of baseline data. Compare with acceptable value ranges and flag points.
- Identify out-of-range values, and develop list (either by use of Smart System or manually) of potential causes.
- Perform analysis of secondary data to narrow down list of causes to a single (if possible) suspect.
- Evaluate the (actual or statistical) cost of continued operation versus shutdown and repair.

Whether shutdown is the result of the recommendation from on-line monitoring, or simply a scheduled overhaul, an effective maintenance program requires a comprehensive inspection and accurate identification and quantification of damage. Without performing a comprehensive unit inspection, the risk of eventual unit failure and performance deterioration increases significantly.

IV. STEAM PATH APPRAISAL

During the maintenance overhaul the mechanical condition of the turbine, particularly the steam path components, must be established. A steam path appraisal is used to identify and quantify mechanisms contributing to unit damage:

A. Historical Data Review

The appraisal effort can be enhanced significantly, and overhaul critical path avoided, if a data package is provided in advance of the unit opening. The data package should include, as a minimum, the following data:

- Steam cycle heat balance(s)
- Performance data collected as described in PERFORMANCE EVALUATION
- Turbine cross-section drawing
- Past inspection reports
- Past preventive maintenance records
- Past corrective maintenance records

A thorough review of the turbine performance and maintenance history is one of the most important aspects of the work. Corrective maintenance records, if properly analyzed, can provide useful trends of component failure and insight into root-cause of failure. Past problems tend to be repeated if not recognized, understood, and actively prevented. This same study is helpful in identifying where the existing test and analysis programs have failed to predict the observed condition of the unit. The study subsequently allows practical suggestions for improving the data monitoring system. After the historical data has been reviewed and evaluated, the appraisal should be planned so that problems suggested by the review can be properly investigated.

B. Opening Appraisal

In order generate meaningful repair recommendations, and to provide baseline data for efficiency comparisons, an appraisal of mechanical conditions prior to performing any repair work should be performed. The appraisal can best be started by timing the Appraisal Engineer’s arrival prior to the removal of the rotor. This permits an important horizontal joint and stationary component/rotor relationship inspection. Radial spring-backed packing, J-strips, and tip seal clearance measurements are required for the appraisal, and these readings must be taken before the rotor is removed. The appraisal value would be further enhanced by the participation of one or more plant engineers who will benefit from a clear awareness of loss mechanisms, analyses of observed conditions, and the investigation into repairs, potential improvements, and upgrades. In addition to its educational value is the fact that equipment owners/users tend to have a greater intuitive insight into potentially unusual operating conditions which may relate to identified damage. Still a further reason for owner/user participation is the generation of team synergy which frequently results in flashes of insight which may not occur in individual inspections.

C. Steam Path Examination

A thorough examination of the critical areas in the steam path is essential to making informed judgments about the efficacy of current operating configurations and for making subsequent determinations about the need for changes to components, application of upgrades, or methods of operation. Exceptional effort should be made at this point to perform a complete and detailed observation of all critical areas and components. Every variation or out-of-character detail should be noted. Thoroughness at this point can save much time later during the evaluation period. A steam path examination should include, as a minimum, the following activities:

- Examine quality of critical aerodynamic components.
- Identify mechanical damage.
- Identify steam path deposits.
- Identify erosion damage.
- Identify seal damage.
- Identify unusual damage.
- Identify and photograph damage.
- Measure and plot patterns of seal wear.
- Review start-up procedures and thermal gradients.
- Determine probability of distortion problems.

D. Evaluation of Steam Path Examination Data

Once the steam path examination is complete, a critical evaluation of the data obtained during the examination must be performed. This evaluation should address all potential mechanisms for damage phenomena observed during the examination. As a minimum, the following activities should be performed:

- Quantify losses caused by mechanical damage.
- Quantify losses caused by steam path deposits.
- Quantify losses caused by erosion.
- Quantify losses caused by excessive tip seal and packing leakage.
- Estimate magnitude and effect of efficiency losses.
- Estimate magnitude and flow capacity effect.
- Reconcile test results are consistent with apparent condition of steam path.
- Identify discrepancies between analysis test results and inspection.
- Develop method for improvement of analyses and diagnoses.
- Develop method for improvement of test procedures.

- Identify performance influencing phenomena, such as previous repair deficiencies or modified design practices
- Discuss with operators, or other support personnel, specific start-up or operating conditions which might contribute to observed unit condition.

E. Prepare Recommendations and Reports

After the steam path examination and the data analysis have been completed, recommendations are made concerning the equipment configuration and operating conditions. In addition, the need for changes in procedures or upgrade of components to improve the operating efficiency of the turbine are disseminated to the responsible parties. When preparing recommendations and reports, the following program is normally followed:

1. Generate recommendations for economically sound repairs; application of component upgrades, and testing and analyses improvements.
2. Provide an oral report to interested personnel, including a discussion of recommended repairs and component upgrades
3. Provide a written report containing the same detailed recommendations given orally.

F. Outage Considerations

While the turbine is out of service for maintenance, the steam path appraisal is used to review and establish engineering guidelines addressing methods to improve efficiency and reliability. While all critical areas of the turbine are subject to evaluation, some of the areas normally under review and consideration would be the following:

- Tighter packing seal clearances
- Reduced tip seal clearances
- Packing and tip seal material changes where beneficial.
- Upgrade of components in the seal areas
- Upgrades in inlet bell seals or snout rings

G. Packing Rubs

Two major events occur that cause seal damage in turbines: distortion and vibration. Due to thermal gradients during startup, turbine inner shells, diaphragms, blade rings, and packing boxes distort and become eccentric. This distortion results in lower half stationary components moving upward towards the rotor. During start-up and shutdown, the turbine rotor is susceptible to vibration as it is brought through its critical speeds. Even though the end bearing vibration may not be excessive, the more critical center span is subject to large deflection. This vibration, in conjunction with thermal distortion of stationary components, results in reduced clearances, interference, and packing rubs. The friction resulting from the packing rub causes localized heating of the rotor, which creates a temporary bow. Because the rotor/stationaries are already in an interference condition, this rub-induced rotor bow exacerbates the packing rub.

When a packing rub occurs, conventional spring backed packing can, to a limited extent, move with the shaft. Rotating blade tips, which are attached to the bowed rotor, interfere with stationary tip seals, which are rigid and therefore receive significant damage due to packing rubs. As important as the temporary rub-induced rotor bow is the fact that most major stationary turbine components become permanently distorted as they age. This permanent distortion is greatly exacerbated by transient thermal distortion related to startup.

H. Distortion Effects

As steam turbines age, the effect of the cyclic thermal variations is frequently observed in the form of distortion of internal parts. These distortion causing thermal variations are most prevalent during transient operating conditions, such as start-up or shutdown of the turbine. The resulting distortion or out-of-round condition is a major cause of excessive internal leakage and an accompanying loss of efficiency. It is, therefore, prudent during an outage to measure and record significant bore diameters in order to determine the amount of distortion present and the effect it has on turbine efficiency. Distortion measurements also identify undocumented machining deviations on both the rotor and stationary components as well as previously unidentified design changes. This investigation also provides an opportunity to permanently update the history of the turbine internals. Recorded outage measurements should typically consist of the following items:

- critical rotor diameters
- packing/spring-backed seal casing bores
- diaphragm/blade ring bores
- tip seal bores

I. Closing Appraisal

After all outage-related repairs and changes have been completed, a closing appraisal is done prior to closing the unit. This appraisal normally evaluates the same parameters as described in Opening Appraisal and Steam Path Examination sections as well as the following items:

- Alignment data (tops off versus tops on)
- Axial and radial clearances
- Condition of the rotor steam path
- Condition of stationary components including diaphragms and/or blade rings

During the closing appraisal, an estimate and quantification by mechanism of anticipated thermal efficiency improvement is performed. This provides a reference for the observed data during the verification of results once the turbine is in operation.

V. POST OUTAGE EVALUATION

After start-up of the unit, a thorough battery of diagnostic tests should be performed at various operating configurations. A review is then performed on the newly obtained operating data, and a comparison made with the data obtained during the opening appraisal. Analyses are also performed comparing the current data to the conditions noted during the closing appraisal. The recorded data from this evaluation is used as a baseline for further performance estimates.

VI. COMPONENT UPGRADES

During recent years many steam turbine components have seen upgrades in materials and design. One area where recently upgraded components have been especially effective is in turbine shaft packing and spring-backed seals, a critical area of leakage and efficiency losses in the steam turbine. Patented Brandon® Retractable Packing has proven extremely effective in reducing rubs and leakage at the shaft.

A. An Advanced Brandon® Retractable Packing

Internal leakage in the turbine steam path can account for as much as 80 percent of the losses affecting turbine efficiency. Worn shaft packing alone are great contributors to efficiency loss as well as operating problems. It is normal to find that excessive leakage caused by worn packing and tip seals exceeds the combination of all losses, particularly in the most sensitive turbine sections such as the interstage shaft seals. In very large turbines, an extra 30 mils in seal clearance can cause as much as 100 BTU/kW-hr heat rate degradation and consequent annual fuel cost increases of $500,000. Besides the direct impact of seal leakage on unit performance, several other areas of turbine operation are affected. Some of these areas are:

- A false indication of high efficiency in the IP section of opposed flow turbines
- Decreased first stage shell pressure
- Excessive turbine flow capacity with subsequent HP section performance degradation
- high extraction temperatures
- Excess heat to condenser

Turbine designers have attempted to reduce shaft leakage by installing seals with reduced flow coefficient that attempt to maintain close clearance between the shaft and the turbine stationary components. Because of component distortion and rotor dynamics, maintaining close clearances without incurring damage to the seals has been an incessant problem with turbine operation. A problem which seemed to have no practical solution, until recently.

Historically, turbine manufacturers have designed packing segments with springs behind them whose purpose was to force the packing close to the rotor into the close-clearance configuration. These springs would allow the packing segments to be pushed away from the shaft in the event of a rub. This design allows for the spring to absorb some of the rub energy. However, this does not resolve the problem of rubbing; it only “softens the blow”, so to speak. Rubbing still results in frictional heating and localized bowing of the rotor, which exacerbates the problem of rubbing, and leads further to tip seal damage.

Logically, if packing clearances could be opened during start-up and shutdown periods--where thermal distortion and rotor critical speed occur--then closed during normal load operation, most severe packing rubs could be avoided. Rubbing of packing, consequential frictional rotor bowing, and damage to packing and tip seals could be minimized and leakage reduced. Many startup problems would be eliminated, and high turbine efficiency could be maintained. This goal has been achieved by the advanced Brandon® Retractable Packing design described herein.

Use of the Brandon® Retractable Packing design to accomplish the objective of large start-up and shutdown clearances with the subsequent reduction of clearances at operating load has minimized packing and tip seal leakage losses found in most operating turbines. In addition, by elimination of rub-induced rotor bowing, startup times have also been reduced. Brandon® Retractable Packing has been installed in over 330 utility and industrial units. On-line performance tests, as well as inspections of operating units have proven the success of the design.

The advanced packing operates in a fashion contrary to conventional packing. In conventional packing, the spring forces force the packing toward the turbine shaft, and as the turbine load increases, the steam pressure adds to the spring force behind the packing. In Brandon® Retractable Packing, the springs forces the packing away from the shaft, and as turbine load increases, the steam pressure behind the packing overcomes the spring forces at a pre-determined load, resulting in small operating clearances.

The basic concept used in the improved packing is that the pressure on the back of the ring is greater than the pressure on the toothed side of the ring. This pressure differential increases with throttle flow and can be used to overcome the spring and friction forces acting on the individual packing segments. By proper engineering of the coil springs between the packing segments, the pressure forces acting on the packing can be utilized to cause the packing to move from a large clearance to a small clearance at a predetermined flow condition that is known to be beyond the condition where significant rubbing is likely to occur. Because of this control over rubbing characteristics, packing can typically be installed with clearances less than the original design. With reduced initial clearances between the packing and shaft, the turbine can achieve increased efficiency, and with decreased damage from packing rubs, this efficiency can be maintained throughout the unit operating cycle.

No modification to the turbine is required to install the improved packing in HP/IP turbines. This allows the installation of the improved packing to be treated as a standard part replacement rather than a modification. The standard design of turbine packing segments is shown in Figure 1, Conventional Packing with the packing springs inserted. In Brandon® Retractable Packing, the major design change is to remove the springs which force the packing ring toward the shaft and install coil springs which force the packing rings away from the shaft Figure 2, Brandon Retractable Packing. The spring geometry, constants, and the hole depths are determined based upon the expected unit operating pressures in each specific location. The revised packing is a direct replacement for the standard packing, since the design changes are made only to the packing.

VII. PERFORMANCE FACTORS

A variety of measurable and unmeasurable benefits result from upgrading to the improved packing. These include the following:

- Reduced startup vibration, and quicker startups
- Decreased shaft packing leakage
- Decreased tip (or shroud) leakage
- Reduced first stage shell pressure, and consequent increased effective control stage efficiency
- Reduction of excess turbine flow capacity
- Significantly longer packing life
- Significantly longer tip seal life
- Reduced boiler emissions
- Reduced fuel handling costs
- Reduced waste handling costs
- Reduced unknowns in LP section deduced efficiency

The decrease in shaft packing leakage now possible because of smaller clearances and the decreased possibility of distortion related damage will create a direct improvement on the turbine section efficiency.

The decrease in tip leakage will result from the avoidance of bowed rotors (normally caused by packing rubs) that result in damaged tip seals. This indirect savings can be expected to exceed even the direct benefits of the improved diaphragm packing clearance.

It is common to find turbine first stage shell pressure lower than design by 5-10 percent. This has the effect of taking energy off the relatively efficient later High-Pressure stages and putting more energy on the first stage (the least efficient stage). The added energy drops the already low first stage efficiency even lower. The improved packing would improve first stage shell pressure, bringing it closer to design values.

Excessive leakage has a secondary effect of increasing the turbine flow capacity. While this may have some side benefits, it also causes some negative efficiency effects across the load range by requiring increased throttling of control valves at normal loads. This causes significantly poorer efficiency. Note that where the excess flow capacity is of value, it may still be available by way of increased initial pressure, 5 percent over pressure being commonly acceptable on most turbines.

The reported results of upgrading to Brandon® Retractable Packing vary and are affected by a number of significant conditions. These include, but are not limited to the following items:

- Alignment of the turbine internals
- Repaired edge thickness, areas, finishes and contours of diaphragm partitions
- Distortion of stationary components
- Condition of blade or bucket steam path
- Location and quality of instrumentation
- Interpretation of results

- The degree to which the turbine packing had been rubbed prior to installation of Brandon® Retractable Packing

It is recognized that other improvements in the steam path to correct losses associated with erosion, mechanical damage, and deposits contribute to increased efficiency. However, in general, the typical improvement from the use of the advanced packing alone has been between one and two percent in heat rate and between two and three percent in kW output. Numerous operational reports support this statement, and are available by request to the author.

VIII. IMPROVED REPAIR PROCEDURES

There are many, sometimes opposing, theories and procedures existing relative to repairing diaphragms and seals. The main dissension centers around the optimum exit edge thickness of stationary blade partitions. This difference of opinion concentrates on improved efficiency with thin edges (0.015-0.020 inch) versus improved longevity in a solid particle erosive atmosphere with thick edges (0.040 inch).

A similar argument relative to the shape of seal teeth, asks whether very tight initial clearances are better than some intermediary clearance value. A sharp packing tooth has a much better flow coefficient than a rubbed tooth. If a packing is installed with too tight a clearance which results in a rub, then it may pass more flow than a packing installed with a greater initial clearance but unrubbed during operation. A decision can be reached by reviewing the past history of the turbine. There are, however, a significant number of other areas in diaphragm and seal maintenance that are often overlooked and which can significantly effect turbine performance and longevity.

Repair procedures have been developed to embrace a number of these considerations. The following list identifies some of the more significant areas normally investigated:

- Bore and hook fit tolerances
- Horizontal joint gaps
- Face setback
- Dishing
- Steam seal face runout and erosion
- Crush pin fit
- Partition surface finish and contour
- Sidewall repairs
- Area checks
- Controlled throat openings pressure side emphasis
- Distortion resolution
- Dowel pin corrections
- Seal ledge corrections
- Key way resolutions
- Root seal repairs
- Resolution of horizontal blade joint
- Material options for repair

All of the above items and others must be taken into consideration and addressed in order to obtain the maximum improvement in steam path efficiency.

IX. VERIFICATION OF UPGRADE RESULTS

Once this program of efficiency upgrade is completed, a review of the current operating conditions is done to verify the efficacy of the upgrade in components and procedures. On the basis of the results obtained from the instrumentation program described earlier and utilizing the results of the steam path appraisals, distortion measurements, and improved parts and repairs, a meaningful verification of operating data can be developed. This verification should address the following points as a minimum:

- Compare current operating data with historical data.
- Compare current operating data with predicted results.
- Compare current operating data with data from other similar upgrades.

X. CASE STUDY

Because of the high cost associated with performing high-precision performance testing, and due to the non-competitive nature of the power generation market until the very recent past; data confirming the theories presented above is typically unreliable. However, in some instances, some power generation equipment users have chosen to invest the time and funds required to perform such tests. The case study below describes the inspection and test procedures implemented to confirm the benefit of Brandon® Retractable Packing. The results of the test and inspection process indicate that the benefits were greater than had originally been anticipated.

A. Unit Description

1) General Electric D5 single reheat configuration
2) Max. Guaranteed rating = 230,810 kW
    - 1,616,000 lbm per hour throttle flow
    - 1,800 psig throttle pressure
    - 1000°F/1000°F throttle temperature
    - Five closed feedwater heaters
    - Exhaust to two-pass condenser at 1.5” HgA
3) Installation of Retractable Packing November 1992

B. Performance Testing-General

This section summarizes the procedure used to measure unit performance both before and after the installation of the Retractable Packing. Performance was tested prior to the unit overhaul to obtain baseline information. Testing following the overhaul was performed in order to assess the effects of work performed.

1. Calibration

Although plant instrumentation was utilized for several parameters during testing, all critical parameters were monitored using test grade instruments calibrated both before and after testing.

Calibrations were made with use of NIST reference standards. All instruments were calibrated at five or more points, with approximately thirty samples taken at each point A list of these parameters can be obtained by contacting the author.

2. Flow Calculation and Cycle Fluctuations

Flow calculations were performed in accordance with ASME Fluid Meters 6 edition and PTC 19.5 in conjunction with the 7th draft of the flow committee. Rapid-load fluctuation of steam flow was limited to ± 0.25% as specified in Table 3.1 of PTC6-1976. All other cycle variations were limited in accordance with ASME PTC6.1.

3. Cycle Isolation

Cycle isolation was performed in accordance with ASME PTC6.1. Details can be obtained by contacting the author.

4. Data Collection

- Critical parameters were monitored using an automated data collection system, with points taken every five (5) seconds.
- Gross generator integrated power was monitored on the existing plant 3-phase JEM MWH meter, and data points were collected at ten (10) minute intervals.
- Auxiliary power data was collected manually at thirty (30) minute intervals.
- Data for other parameters were collected manually at ten (10) minute intervals.

5. Test Runs

Each test (pre-overhaul and post-overhaul) consisted of five (5) separate runs of approximately two (2) hours duration at Valves Wide Open (VWO) flow.

6. Test Corrections

Gross turbine heat rate and gross generation were corrected to the following design conditions:

- Throttle Pressure
- Throttle Temperature
- Reheat Temperature
- Reheater pressure Drop
- Exhaust Pressure

C. Comparison of Pre-Overhaul & Post-Overhaul Test Results

The following table summarizes the results of testing performed both before and after the turbine overhaul:

Table 1 -- Comparison of Pre- and Post-Overhaul Test Results

TEST PARAMETER	UNITS	PRE-OVERHAUL	POST-OVERHAUL	Δ (%)

		RESULTS	**RESULTS**	
LOAD	kW	247,168	256,979	3.97%
CORRECTED LOAD	kW	249,102	257,713	3.46%
GROSS TURBINE HEAT RATE	BTU/kW-hr	9,057	8,553	-5.56%
CORRECTED GROSS TURBINE HEAT RATE	BTU/kW-hr	8,987	8,546	-4.91%
HP TURBINE EFFICIENCY	%	80.05	81.79	2.17%
APPARENT IP TURBINE EFFICIENCY	%	88.03	90.15	2.41%

D. Comparison of Pre-Overhaul & Post-Overhaul Inspection Results

A steam path audit was performed at the beginning of the overhaul (see Table 2 -- Pre-Overhaul Inspection Losses Summary), before any work was performed. This was in order to obtain a baseline report of the unit condition. Following the overhaul, before the unit was re-assembled, another audit was performed (see Table 3 -- Post-Overhaul Inspection Loss Summary) in order to quantify the effects of the work performed.

1. Pre-Overhaul Inspection

Table 2 -- Pre-Overhaul Inspection Losses Summary

LOCATION	PACKING LOSS (kW)	TIP SEAL LOSS (kW)	DEPOSIT LOSS (kW)	DAMAGE LOSS (kW)	EROSION LOSS (kW)	EDGE THICKNESS LOSS (kW)	TOTAL LOSS (kW)	TOTAL LOSS (BTU)
N1	471						471	18
HP STAGES	1,011	1548	8	0	0	0	2,567	100
N2	604						604	23
IP STAGES	239	1120	11	54	234	0	1,658	64
N3	150						150	6
LP STAGES	565	1655	1136	0	0	0	3,356	131
TOTAL	3,040	4,323	1,155	54	234	0	8,806	342

2. Post-Overhaul Inspection

Table 3 -- Post-Overhaul Inspection Loss Summary

LOCATION	PACKING LOSS (kW)	TIP SEAL LOSS (kW)	DEPOSIT LOSS (kW)	DAMAGE LOSS (kW)	EROSION LOSS (kW)	EDGE THICKNESS LOSS (kW)	TOTAL LOSS (kW)	TOTAL LOSS (BTU)
N1	355						355	13
HP STAGES	397	12	0	0	0	0	409	16
N2	260						260	10
IP STAGES	103	212	0	13	23	66	417	16
N3	74						74	3
LP STAGES	565	798	0	0	0	0	1,363	53
TOTAL	1,754	1,022	0	13	23	66	2,878	111

3. Comparison Between Pre- & Post-Overhaul Inspection

Table 4 -- Comparison of Losses, Pre- & Post- Overhaul Inspection

LOCATION	PACKING LOSS (kW)	TIP SEAL LOSS (kW)	DEPOSIT LOSS (kW)	DAMAGE LOSS (kW)	EROSION LOSS (kW)	EDGE THICKNESS LOSS (kW)	TOTAL LOSS (kW)	TOTAL LOSS (BTU)
N1	116	0	0	0	0	0	116	5
HP STAGES	614	1,536	8	0	0	0	2,158	84
N2	344	0	0	0	0	0	344	13
IP STAGES	136	908	11	41	211	-66	1,241	48
N3	76	0	0	0	0	0	76	3
LP STAGES	0	857	1,136	0	0	0	1,993	78
TOTAL	1,286	3,301	1,155	41	211	-66	5,928	231

E. Reconciliation of Test and Inspection Data

Differences can be seen between test data and inspection data. Parameters affecting this deviation are listed below. Details of the reconciliation can be obtained by contacting the author.

- Conservative calculation of tip seal flow coefficients which generally do not account for sharpness of teeth. Typical audit calculations assume some rubbing, and therefore assume rounded teeth with higher flow coefficient. Approximate value in heat rate improvement ≈ 46 BTU.
- Improved design tip seals, with an improved flow coefficient, were installed. This improved flow coefficient was not accounted for in the steam path audit calculations. Approximate value in heat rate improvement ≈ 19 BTU.
- Replacement of one LP feedwater heater. Actual heat rate effect difficult to assign, as testing was not designed to monitor these parameters. It is unlikely that this particular Low-Pressure heater contributed significantly to overhaul heat rate improvement.
- Cycle leakage improvements are difficult to assign. Some improvement in cycle heat rate may have been achieved as a result of valve replacement and/or repair.

F. Current unit operating condition

Of great importance is the ability for an upgrade component to provide sustained high efficiency levels. There is currently no formal data available to confirm the current operating condition for this case study, in part because the user has had little incentive to invest time and money into regular monitoring. The unit is operating very well, with no indication of significant losses. Therefore, no regular performance monitoring is being performed. Future publications by the author will formally address the unit's current condition.

XI. CONCLUSIONS

Improving reliability and maintaining high levels of steam turbine efficiency through improved diagnostic procedures, improved repair methods, and upgraded steam path seals can provide immediate and long term economic benefit to the owners and operators of steam turbines. These benefits come in the form of improved startups, increased capacity, and reduced operating costs.

Performance testing and verification of results are very important; however, it should be emphasized that the source of all justification for improved repair procedures and upgraded steam seals is a thorough and effective steam path audit prior to committing resources to the effort.

One of the most important factors in the quest for improved turbine efficiency is the condition of the steam path sealing systems. The magnitude of efficiency losses in aging steam turbines can become large; and the costs and environmental impact associated with these losses are increasing in importance. These systems should then naturally be the focus of efforts to improve the design and effectiveness of the components involved. The effects of steam path losses can be accurately calculated with reasonable effort, and the results can be used for effective maintenance planning.

The prospect of continued rising operating costs and environmental pressures for the owners and operators of steam turbines presents the challenge of continuously seeking cost effective means of improving the efficiency and longevity of the equipment. Fortunately, modern materials and designs now provide cost effective alternatives to critical components which in the past have caused the most problems for equipment owners. Test results indicate that component upgrades such as Brandon® Retractable Packing contribute significantly to improved unit efficiency, and thus can result in significant decreases in operating cost and the environmental impact of operation.

Figure 1, Conventional Packing

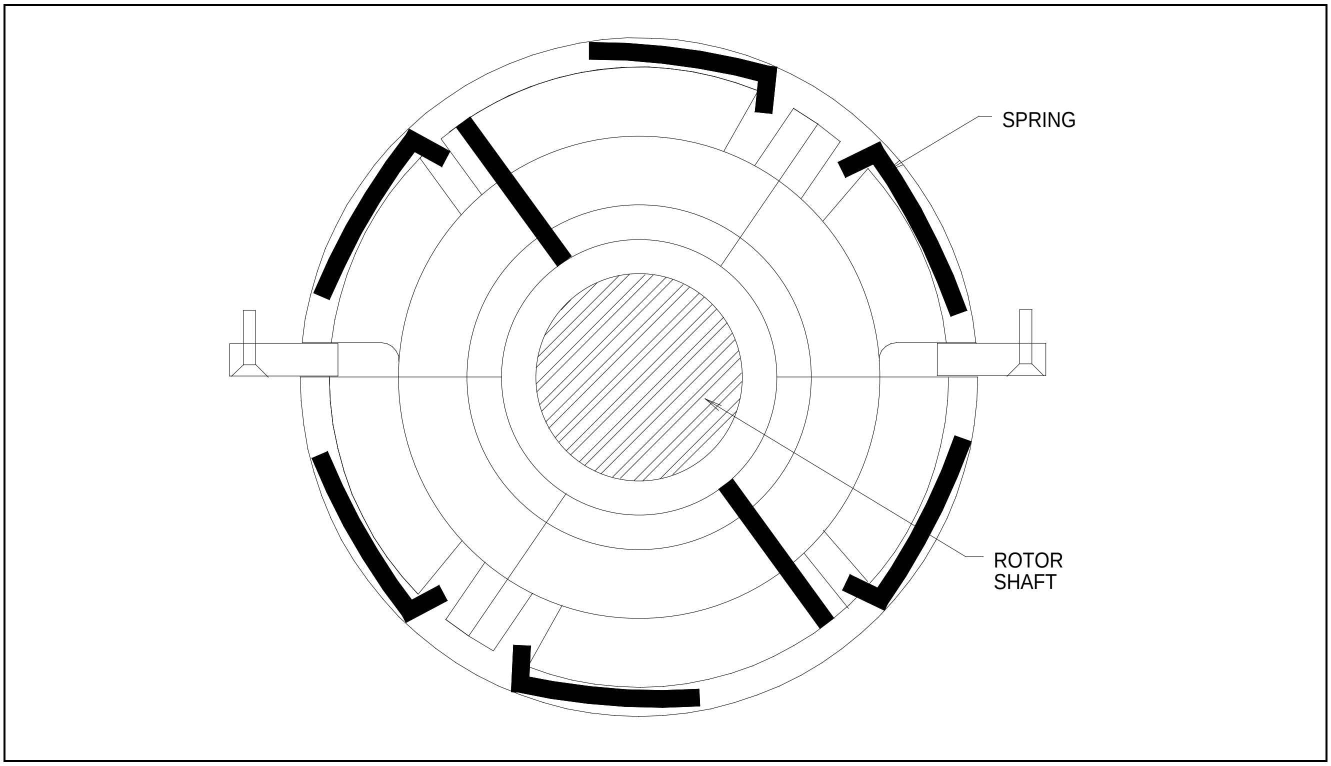

Figure 2, Brandon Retractable Packing