Steam Turbine 34.5-Inch Low-Pressure Section Upgrade

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Steam Turbine 34.5-Inch Low-Pressure Section Upgrade

Introduction

Today’s energy market demands increasingly high performance levels in both the efficiency and reliability of power generating equipment. The efficiency of the entire power plant is largely dependent on the energy conversion in the steam turbine. The low-pressure section alone is responsible for delivering up to 50% of the output. Turbine performance is affected by erosion and wear due to turbine aging.

In addition to erosion and wear, long-term low-pressure section reliability can be affected by stress corrosion cracking (SCC) of the low-pressure rotors. Serious incidents of SCC have resulted in extended outages due to unexpected rotor repair work, and in many cases the engineered solution has been rotor replacement.

To address current performance and long-term reliability, GE recommends replacing the original 30-inch last stage bucket’s steampath design with a new steampath having 34.5-inch active-length last stage buckets (LSBs). Longer last stage buckets—which increase annulus area and reduce exhaust losses—are features of the new design targeted to increase plant output. New rotors extend the life of the plants and extend outage intervals. Power plants can remain competitive by increasing the efficiency and reliability of the low-pressure sections of steam turbines.

Fleet Demographics

The targeted fleet for this 34.5-inch low-pressure section upgrade contains the numerous GE units that utilize the original 30-inch LSB design in 2-, 4- or 6-flow low-pressure casing designs. Most of these turbines are over 30 years old and utilities are depending more and more on these workhorse units. (See Figure 1.)

As an example, Figure 1 shows that 30% of the capacity was from units that were greater than thirty years old. Most of these units suffer from degraded performance and may require increased maintenance to ensure continued reliable operation.

Reasons for Low-Pressure Section Upgrades

Since much of the GE fossil fleet of steam turbines has more than 20 years of service, GE Energy can help improve performance and extend the life of these turbines by installing a modern steampath with advanced aerodynamic component design—which increases turbine reliability and reduces maintenance and life cycle costs. This bundled offering of advanced low-pressure (LP) steampath and component designs is intended to improve the output and reliability of fossil steam turbines.

Performance is improved by installing a new steampath with advanced technology; recovery of aging losses due to plant erosion and deterioration; and increased output attributed to increased annulus area of the last stage buckets. The LP section alone can generate up to 50% of the total plant power.

Our new, more efficient steampath results from an improved aerodynamic steampath design and advanced sealing technologies. Recovery of performance losses, attributed to unit aging, is realized as new parts replace older eroded and worn parts. Over the life of the turbine, erosion and wear typically take a toll on both reliability and efficiency. Quoted expected improvements are due to steampath efficiency increase and exhaust loss decrease, and do not include the improvement from replacing aged equipment.

Both the increased output (with no additional steam flow) and the increased annulus area are realized with longer last stage buckets. The longer LSBs provide reduced exhaust velocity, which results in lower exhaust losses and improved heat rate. The increase in turbine output is a function of back-end loading and backpressure. This increase varies for each customer and varies throughout the year.

Reliability is enhanced through new, improved components and materials, and mitigated stress corrosion concerns. Typically, the performance improvement package becomes most attractive when the owner/operator is already considering a major repair due to a maintenance issue, or when there is a need to significantly extend turbine life.

Figure 1. Utility dependence on older units
Description of Section Replacement

The low-pressure conversion discussed here involves replacement of the entire LP section.

While the exhaust hood is retained, minor modifications to the hood are required to reduce exit losses. The advanced features of the new design and the major upgraded components include:

- Modern 34.5" active-length last stage buckets providing increased exhaust annulus area
- Advanced aerodynamic designed bucket and diaphragm blade profiles
- Advanced sealing technologies utilizing shaft brush seals, and integral covered buckets with multi-tooth spill strips on non-margin stages
- Low-pressure inner casings with modern features, including improved inlet exhaust aero designs and exit contour steam guide design
- Modern monoblock rotor with stress corrosion cracking concerns mitigated

Plant Level Considerations

Since the new LP sections are designed specifically for the original unit, several plant-level design considerations must be taken into account during the steampath aerodynamic optimization. The following plant-level constraints must be incorporated into the new design to ensure compatibility with the existing design:

- The existing exhaust hoods typically are retained due to large cost/cycle to replace. Therefore, the new parts (rotor, diaphragms, inner casing) must fit into existing hardware and maintain hardware interface points.
- The actual range of flow and condenser pressure must be used to determine optimal design. Customers typically provide an average annual condenser backpressure profile and current heat balance flows. Any new steam conditions can be modeled, and output based on backpressure profiles is provided by GE.
- The new design must match existing feedwater pressures. The thermal conditions at the inlet to the low-pressure section and at the stages with extractions have to be maintained to reduce the impact on the rest of the plant. The pressures at the extraction stages have to remain compatible with the existing heater design. Similarly, significant changes to the LP inlet pressure will impact the turbine intermediate pressure (IP) section performance. The variables in the optimization include number of stages, reaction level, bucket active lengths, inner ring diameters, and steam velocity angles.
- The upper stage areas are designed to match the original areas as much as possible. The bottom two extraction pressures decrease because of the larger stage areas. The new pressures need to be reviewed to insure they are acceptable to the balance of plant. The physical location of the extractions is unchanged. The inner casing change-out requires extraction piping to be cut from the 30" inner casing, and welded to the new inner casing.

Design Features

Advanced aerodynamic features include the following key elements: an improved design steampath; advanced sealing technology and optimized clearances; integral covered buckets, longer last stage bucket design; inlet and exhaust inner casing; and steam guide designs.

Advanced Component Design Steampath

The group stages in the low-pressure design build on GE’s Dense Pack™ technology: the reaction levels are raised; the active lengths and root diameters are optimized; there is a reduction in blade count; and the blades have an aerodynamic contour.

The following two aspects of the group stage steampath design were considered:

- Optimization of the thermodynamic/aerodynamic design of the stages (including number of stages, inner ring diameters, active lengths, and reaction levels)
- Applicability of available steampath design features used mainly for sealing (such as brush seals and integral cover buckets)

Figure 2 shows an example of a contour plot of reaction level vs. gamma angle (exit angle of the steam leaving the bucket). Similar contour plots were created for the other variables and used to determine the optimum steampath design parameters.

This analysis resulted in stages with higher bucket reactions and increased root diameters. The number of stages remained the same as in the existing 30-inch LSB steampath design. The
performance gain for additional stages was small and resulted in reduced axial span for the inlet and exhaust, leading to higher losses in these areas.

The move toward higher reaction on the buckets increases the need for good sealing across the bucket tip and rotor packing to reduce leakage. To minimize the leakage across the tip, integral cover buckets with vernier seals are included as part of this replacement. To minimize leakage across the packing rings, brush seals are used on the higher-pressure stages. The remaining stage packing rings have slant teeth. The improved packing sealing—along with the higher bucket reaction—reduces root intrusion losses and allows for the reduction or elimination of the steam balance holes. This reduction in leakage at the tip, root, and packing results in an overall reduction in losses in these areas.

The computational fluid dynamic (CFD) codes available today allow for a simplified, accurate solution to a three-dimensional viscous flow equation for all stages of the steam turbine. The advanced design steampath (ADSP) is the result of an extensive analytical and testing program and utilized many of the concepts from GE’s aircraft engine design technology. The results of these efforts are steampath components with the following characteristics:

- Variable tangential or compound lean (Figure 3) is used in the nozzles when it produces a significant gain in overall stage efficiency. GE’s studies have shown that if the vortexing and lean are done in the proper combination, they can reduce the secondary flow vortices entering the bucket, significantly improving bucket efficiency. This, when combined with redistributing the flow radially and leaning the nozzle, has a significant effect on the overall nozzle efficiency.
- The radial flow distribution is tailored to maximize efficiency based on the individual stage geometry and operating conditions.
- The total nozzle surface area has been reduced relative to a conventional design by using fewer partitions (in some cases a 50% reduction) in each row with better aerodynamic shapes that retain the same total mechanical strength as a conventional design. This provides a net reduction in profile loss with no loss in mechanical integrity.
- Root reaction is increased in varying degrees to improve bucket root performance. Tip reaction is generally decreased relative to a free vortex design to reduce tip leakage.

Advanced Sealing and Optimized Clearances
To reduce the stage leakage losses and improve stage efficiency, the new steampath design utilizes advanced tip, root, and shaft clearance controls. Vernier tip seals are used to minimize tip leakage, as shown in Figure 4.
Multiple teeth on the robust spring-backed spill-strip design increase the flow restriction for all operating points. The tip clearances are tightened on stages with vernier seals and reduced steam velocity and reduced leakages are realized. (See Figure 5.)

At the bucket vane root, an added large radius root deflector minimizes root leakages, improves the flow, and minimizes velocity between the stationary and rotating parts. (See Figure 6a.) In addition, axial clearances are optimized for added efficiency (through reduced carryover and improved flow path contours). Figure 6b shows the CFD employed to optimize the large radius root deflector geometry.

GE has been applying brush seals for inter-stage and end packing shaft sealing in both fossil and nuclear applications. Experience to date has been successful and shown the following:

- Brush seals noticeably improve efficiency and do not degrade due to moderate packing rubs
- Brush seals maintain their durability throughout typical operating pressure transients
- Rotor wear is limited to surface polishing of the rotor with no adverse affect on rotor stability when properly implemented

GE’s standard brush seal packing design couples a single brush row with standard high-low packing teeth in order to ensure reliable sealing throughout the life of the seal. (See Figure 7 and 7b.)

The brush seal design has been consistently improved as a result of real-world field experience. The latest improvements include improved bristle stiffness, reduced cold bristle clearance, reduced bristle diameter, and improved bristle stability. A full rotor train stability evaluation is conducted to determine the optimum number of stages to apply brush seals.

**Integral Covered Buckets**

The group stages of the LP section incorporate integral covered buckets (ICBs). ICBs provide a continuous cover surface above the tip of the bucket row. This feature—in combination with various advanced tip vernier seal designs—provides more efficient sealing, which results in improved section efficiency as well as a more robust mechanical design.

ICBs also further reduce an already low problem rate caused by either bucket or cover vibration. This reduction is due to the suppression of the fundamental tangential bucket mode of vibration through the continuous coupling achieved at the bucket covers.

ICBs replace the traditional peened-on cover and tenon design, eliminating the need for cover removal and re-peening when tip
seal maintenance is required (due to rubbing during start-up and shutdown).

**Last Stage Bucket Design: 34.5-Inch Active Length**
The modern 34.5-inch last stage design builds on GE’s decades of experience of utilizing modern design methods to achieve optimum efficiency and reliability. The new bucket uses an advanced material (Jethene®) that eliminates the need for welded erosion shields. Instead, a hard, erosion-resistant area is incorporated into the blade’s leading edge that allows the blade to be “self shielded.” The buckets are also available with a Stellite® erosion shield.

The latest evolution of the 34.5-inch design provides a unique over-twisted vane. At operating speed, the bucket untwists to the optimum aerodynamic position for maximum performance and minimum mechanical loading on the covers and bucket tip. The design uses a continuously coupled cover connection at the bucket tip, and an articulated nub-sleeve loose connection near the mid vane. (See Figure 8.)

Through the continually coupled cover design, and loose tie wire, both bucket modal suppression and structural damping are achieved. The buckets have the necessary characteristics to suppress response caused by off-design conditions or buffeting at very low load or high exhaust pressure. In addition to damping, the bucket is also tuned to maintain its natural frequencies well removed from known sources of potential stimulus (such as multiples of running speed). The 34.5-inch is the premier last stage bucket offered on GE’s large fossil fleet because of the proven reliability, sound design, and excellent performance.

The new 34.5-inch LSB design increases the annulus area by 24%, compared to the existing 30-inch LSB. Depending on condenser pressure and flow, this increased annulus area can lead to significant improvement by allowing a reduction in exhaust loss.

Additional benefit can be realized by a new, modern LSB designed with advanced three-dimensional computational fluid dynamics (CFD) flow modeling, optimized blade inlet angle to minimize losses, and reduced exit velocities. (See Figure 9.)

The new LSB design includes optimized nozzles for improved stage efficiency, as well as longer buckets (for L-1 and L-0 stages) for reduced annulus velocities. Increased reliability and performance are achieved through improved stage efficiency and additional performance improvements are realized through reduced exhaust losses. This design also results in optimized flow distribution and reduced exit velocity.
GE’s experience with 34.5-inch last stage buckets is significant, as shown in Table 1. There are a total of 132 turbines with the 34.5-inch last stage bucket and 299 rows. They first shipped starting in 1988 and this total continues to grow.

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<td>1991</td>
<td>75-182</td>
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<td>120-412</td>
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<td>33</td>
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<td>1988</td>
<td>563-860</td>
</tr>
<tr>
<td>Total</td>
<td>132</td>
<td>299</td>
<td>1988</td>
<td>75-860</td>
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Table 1. 34.5” Last stage bucket experience

**LP Inner Casing Inlet Design**

Using computational fluid dynamics (CFD) and finite element analyses, the inlet configuration of the inner casing has been redesigned to optimize performance. (See Figure 10.)

By utilizing entrance flaring, flow guides (Figure 11) and aerodynamic flow splitters, the flow velocity into the first stage has been made more uniform, improving the first LP stage efficiency.

**Exhaust Steam Guides**

The 34.5-inch low-pressure section upgrade retains the current hood while installing larger internal components. If proper precautions are not followed, installing a larger LP steampath into an existing exhaust hood can have a detrimental effect on efficiency. The larger steampath can restrict the flow from exhausting to the condenser,
thus increasing the exhaust losses for the last stage. To address concerns about cramped hoods, GE used CFD analysis coupled with design validations to improve the design of hood exhaust steam guides in order to minimize losses. (See Figure 13.)

Condenser Backpressure – Effect on Efficiency Improvements

The 34.5-inch low-pressure section upgrade results in an increase in output and heat rate. The improved performance comes from two sources:

- Improved LP section efficiency
- Reduced exhaust velocities

The efficiency improvement is a direct result of the advanced steampath features discussed previously in the Design Features section of this document. This increased efficiency results in a moderate year-round performance improvement. More importantly, coupled with this efficiency gain is a significant performance improvement resulting from the reduced exhaust loss inherent to the longer 34.5-inch LSB.

Exhaust loss refers to the energy lost to the condenser as a result of the steam velocity going into the condenser. The faster the steam leaves the last stage buckets, the greater the energy lost. The key parameters are condenser backpressure, exhaust area, and flow. Based on the thermodynamic characteristics of steam turbines, low backpressures result in a high velocity exhaust steam. At higher flows and smaller exhaust areas, higher exhaust velocities are produced. Since the backpressure is a function of the plant cooling system, and the flow is a function of the initial plant design, the only cost-effective way to reduce the velocity is by increasing the area. This is achieved by increasing the last stage bucket length.

All steam turbines experience a range of backpressures over the course of a year and are primarily dependent upon the heat rejection capability of the condenser cooling water. Low backpressures typically occur during the winter and higher backpressures typically occur during the summer. With the advanced steampath being proposed by this offering, the exhaust annulus area is increased with the longer LSB and thus the exhaust velocity is reduced. During the winter when velocities are high, reducing the exhaust velocity will result in less exhaust loss and thus better performance—for instance, less waste heat and more MW. In the summer when backpressure is typically higher and exhaust velocities are lower than during the winter months, the upgraded steampath with increased annulus area further slows the exhaust steam. However, the gain in summer is less than the gain in winter. Generally speaking, the minimum exhaust loss occurs when the exhaust velocity is about 600 ft/s. Running below this value results in a higher loss due to operation in the “turn-up” region of the exhaust loss curve. (See Figure 14.)

There may be times when increased exhaust loss caused by very low annulus velocities (below 600 ft/sec) actually causes a decrease in power and poorer heat rate. Calculations have shown that this is more than balanced by the increase in steampath efficiency.
As shown in the typical performance improvement graph in Figure 15, there is a significant performance gain both in summer and in winter. Computational Fluid Dynamics (CFD) was used to analyze the inlet geometry. Two different studies were performed. The first study identified features to improve the flow profile of the inlet. The second study determined the impact of decreasing the inlet span, i.e., increasing the inlet velocity.

Figure 15. Typical performance improvement

Based on the analysis, several improvements have been made to the inlet profile of the new inner casing. These improvements include entrance fairing, inlet flow guides and aerodynamic flow splitters. Figure 15 shows the CFD results for the baseline flow pressure distribution vs. the flow pressure distribution predicted for the redesign. Elimination of protrusions into the flow and a smooth inlet transition result in an inlet design that has a lower overall pressure drop and more evenly distributed flow.

Implementation of this upgrade results in a typical unit performance improvement of 1.5% total output in the winter (assuming an exhaust pressure of 2.0” HgA) and 0.5% in the summer (at an exhaust pressure of 3.5” HgA). The actual benefits of this uprate depend on unit-specific site and turbine data such as operational status, design steam conditions and flows, and actual operating exhaust pressure. GE will be pleased to calculate the performance gain for any specific unit.

Figure 16 shows the lower exhaust loss due to the larger last stage for a typical unit. The figure does not show the effect of improved low-pressure efficiency due to the modern steampath.

Figure 16. Decrease in exhaust loss

Rotor Stress Corrosion Cracking Mitigation

Stress corrosion cracking (SCC) results from tensile stress acting on a susceptible material that is operating in a “corrosive” environment (See Figure 17.)

Figure 17. Factors affecting stress corrosion cracking
The cracks are brittle in nature and may be either intergranular or transgranular depending on the material and the environment. A distinguishing feature of stress corrosion cracking is brittle failure at stresses substantially less than those necessary to cause failure in a “non-contaminated” environment. GE provides recommendations regarding steam purity to reduce the likelihood of developing SCC.

**Once-through vs. Drum Type Designs**

In supercritical fossil units with once-through boilers, all the contaminants entering the boiler are carried over into the steam delivered to the turbine. The feedwater and any contamination introduced during the treatment process are carried directly into the boiler and then into the turbine, with no separation of dissolved solids as in drum type subcritical boilers.

The incidence of SCC in the low-pressure sections of units operating with once-through boilers has been much higher than in units with drum type designs. However, there has been a rise in SCC indications on drum type units. SCC is a time-dependent phenomenon with some cracks developing in supercritical units after approximately 25 years. The crack initiation period on drum type units may simply be longer than for once-through boilers, all other factors being equal.

**GE Recommended Inspection and Repairs**

GE has issued inspection recommendations for low-pressure rotors in Technical Information Letter 1277.

Repairs to rotors damaged by SCC can range from removal of cracks by grinding to extensive and time-consuming weld repairs. Weld repairs include fine-line welding of new split rings following removal of the damaged dovetail and replacement of the buckets. In some cases, the damaged dovetail can be removed by machining and a new dovetail machined into the remaining wheel stock. New long-shank buckets are then installed.

**Improved SCC Resistance**

The typical technique used to mitigate the initiation of SCC is to reduce the operating stress, utilize less susceptible materials, and contain the influx of potentially harmful contaminants. The 30” to 34.5” conversion incorporates these features to improve the SCC resistance of the design. Finite element analyses have been used to develop new bucket and rotor dovetails with significantly lower peak stresses in the fillet regions. (See Figure 18.)

In addition, some rotor dovetails may be shot-peened to induce a surface compressive stress providing an additional level of protection.

**Design Validation**

The testing program used to verify predicted efficiency gains for the new concepts was conducted in the single-stage subsonic air turbine and multi-stage low speed research turbine at GE Energy’s Aviation business.

To verify the performance of the 30-inch to the 34.5-inch retrofit, GE conducted a test program in the recently renovated Low-Pressure Development Turbine. (See Figure 19.) A 42% scale of the last four stages of the 34.5-inch steampath was tested along with an exhaust hood scaled from a typical 30-inch machine. Exhaust loss performance predictions were confirmed by testing over a wide range of annulus velocities (VAN), ranging from 200 ft/s to 1200 ft/s.
This high accuracy testing confirmed that the GE 34.5-inch last stage bucket and its redesigned steampath can be applied inside the 30-inch exhaust hood with excellent and predictable results.

**Conclusion**

With the large number of older utility units operating in the marketplace, refitting new LP sections offers an attractive option that provides increased power, improved heat rate, and increased reliability by eliminating potentially costly rotor repairs. This also yields an improvement in emissions, and enhances the utilization of existing sites, which already have appropriate permits.

GE’s new offering of replacing an existing 30-inch last stage bucket steampath with a new steampath incorporating the 34.5-inch last stage bucket can provide increased output. The amount of expected increase for a particular unit depends on back-end loading and is highly dependent on the range of backpressure that the unit experiences throughout the year. Decreasing the exhaust annulus velocity—but avoiding the turn-up region—results in a significant reduction in total exhaust loss.

It is necessary to establish a favorable economic analysis that is focused on the size and characteristics of the existing power plant. The analysis may show uprating to be an attractive option relative to either continued operation as is, or a new plant. Uprating may also be attractive for a coal-fired facility relative to environmental compliance of fuel switching.

**References**


**Acknowledgement**

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