Performance Uprate of a Geothermal Steam Turbine Case Study: Brady Power Low Pressure Turbine

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ABSTRACT

The output of a low pressure steam turbine operating in a geothermal power plant has been increased 10.9 % by performing an efficiency uprate. The performance of the turbine was studied, resulting in a design for re-optimizing the steam path. New high-efficiency components were blended with existing turbine parts to achieve large output gains at minimum cost. Because the uprate was performed by a non-OEM, the analysis and manufacturing techniques were specifically tailored for the aftermarket. The work was completed on the spare turbine components, thereby allowing the plant to continue operation while the uprated parts were being manufactured. The predicted output gains were confirmed by field performance tests of the existing and uprated turbines.

Introduction

The turbine uprate project took place at the Brady Power Partners (BPP) geothermal power plant in Fernley, Nevada. The plant uses a double flash system in which the steam produced by the first flash is used to feed two high pressure turbines, and the steam from the second flash supplies a single low pressure turbine. The uprate work was done on the low pressure unit only.

BPP contracted with Elliott Aftermarket Technology Service (ATS) to provide an uprate to re-optimize the turbine and to maximize output.

Description of Existing Turbine Design

The subject turbine is a double flow condensing design. It was originally manufactured by General Electric for Naval ship propulsion. The turbine had been modified before reapplication to it's present geothermal power generation duty. Figure 1 shows the existing turbine cross-section prior to the uprate redesign.

At the time of the uprate, the existing turbine was operating at the following conditions:

Generator output (Kw)	6175
Inlet pressure (psia)	21.04
Inlet temperature (°F)	Saturated
Exhaust pressure ("HgA)	2.34
Throttle flow (#/hr)	178,873
Speed (rpm)	4352

The existing LP turbine was a 4 stage double flow with a 7.0" last stage bucket height. The original 6 stage Naval propulsion design had been modified by removing the first 2 stages and rotating parts of the astern drive elements from each flow direction.

Uprate Process

The uprate process began when Elliott ATS engineers traveled to the BPP plant to take detailed measurements of the spare rotor and nozzle diaphragms for the LP turbine. Specific measurements of both the stationary and rotating components were taken, including: throat dimensions, blade height, pitch diameter, blade axial width, interstage and end seal clearances, and stage spacing. Using the dimensions from the steam path, a performance model was built using an Elliott-proprietary turbine analysis program. See reference 1 for more information concerning the turbine performance program. The performance model was the foundation of the uprate engineering analysis,

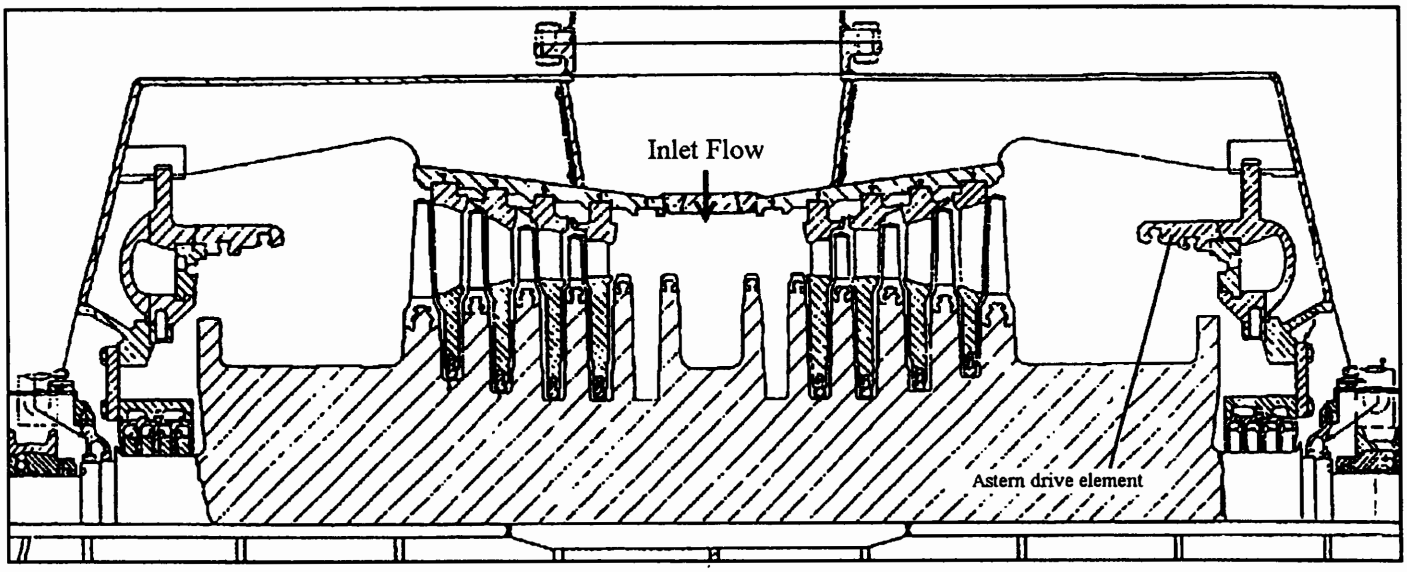

Figure 1. Geothermal turbine before uprate.

allowing performance enhancement options to be realistically explored. These calculated improvements were then reviewed by BPP to determine the financial feasibility of the uprate proposal options.

Once the uprate package was selected by BPP, the spare rotor, spare nozzle diaphragms, and a spare (duplicate) casing were shipped to the Elliott service shop where the work was to be performed. The LP turbine remained in operation while the uprated hardware was being manufactured.

After the performance calculations were completed, the mechanical analysis of all critical components was done. The results of the performance model provided the stage loads and operating conditions of all components (including *new* loads on the existing hardware). The structural integrity of the uprate design was confirmed to meet all Elliott design criteria for new equipment. After the aerodynamic and mechanical designs were completed, manufacturing drawings were created.

The engineering, design, and project management for the uprate were performed by Elliott ATS at the company headquarters in Jeannette, Pennsylvania. Manufacturing of the uprated parts and refurbishment of reused components was done at the Elliott service shop in Jacksonville, Florida.

Sources of Existing Steam Path Efficiency Loss

The performance study done on the existing configuration showed that the flow through the turbine was limited by the first stage flow area. Because the turbine had originally been designed for higher pressure (lower specific volume) steam, the unit was not able to pass sufficient quantities of low pressure (high specific volume) steam to meet the output requirements of the customer. The first and last stages also were very heavily loaded, resulting in poor stage efficiency.

The entire steam path was analyzed using the performance model to determine sources of inefficiency and areas for redesign. The existing problem areas will be discussed separately below.

Inlet Plenum of Turbine—As shown in Figure 1, the steam enters the turbine at the center of the casing. The existing design provided no guidance for the steam, which experienced a sudden expansion into the inlet plenum area. In addition to the pressure loss caused by the sudden expansion, there were 4 exposed (unused) disks left over from the original Navy design which caused further disruption of the inlet flow and also caused windage loss.

Early Design Blading—The existing GE turbine design dated to the early 1940's. These turbines were originally intended for use on Navy Cruisers during World War II. The existing LP turbine employed early design airfoils throughout.

The airfoil cross-sections typical of an early turbine stage design are shown in Figure 2. The nozzle blade is a low-aspect-ratio, although high strength design. Note that aspect ratio is defined as blade height divided by chord length. Low aspect ratio contributes to reduced efficiency in the nozzles. On the rotating blades, the airfoil profile can be described as having "circular arc/straight line" construction. The sharp curvature changes that occur at transitions from radius to straight surfaces cause rapid acceleration and deceleration of the steam flow. The rapid deceleration of the steam flow on the suction side of the blade near the exit of the blade passage causes early boundary layer separation, resulting in increased efficiency loss.

Figure 3, taken from reference 2, shows the Mach number distribution plot for a typical early bucket design. The vertical axis is Mach number, which is a non-dimensionalized steam flow velocity along the surface of the airfoil. The horizontal axis denotes the axial distance through the bucket flow path. The bucket profile has been superimposed on the chart for refer-

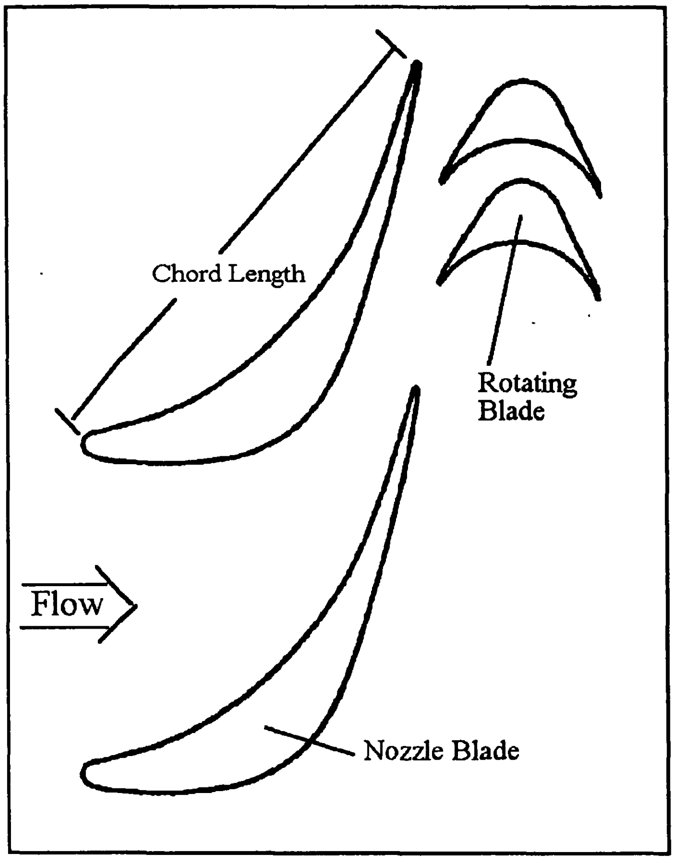

Figure 2. Early design stage.

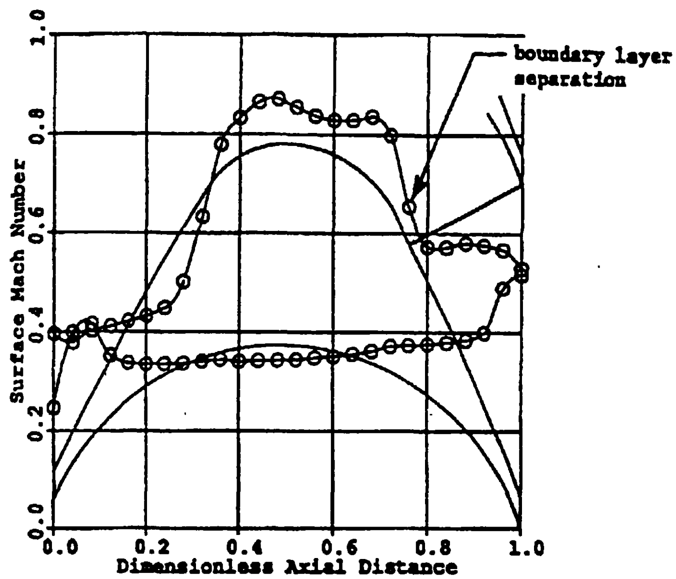

Figure 3. Mach number distribution. Typical of Early Bucket Design

ence. The upper and lower curves on Figure 3 correspond respectively to the velocities on the suction and pressure sides of the blade. Note the rapid increase and decrease in surface Mach number on the suction side of the blade.

Lack of Seals—The existing staging did not incorporate bucket tip seals into the steam path. This allowed a significant portion of the steam to leak around the buckets, and as a result not contribute to driving the rotor.

Heavily Loaded Last Stage—The existing steam path design placed too much thermodynamic loading (i.e. available energy) on the last stage. In effect, the last stage was too small to efficiently handle the amount of steam required at the given operating conditions. As a result, higher bucket leaving losses and exhaust hood losses occurred because of the higher steam velocity exiting from the last stage bucket. The loading situation on the last stage is typical of the tradeoff that is often made between economy (use of an existing surplus Navy turbine in this case), and the high efficiency of a turbine custom-designed for the operating conditions at hand.

Exhaust Hood Losses—The exhaust hood of the subject turbine was especially inefficient due to the presence of a portion of the original astern drive element left over from it's Naval propulsion design. This large casting disrupted the smooth flow of steam from the last stage bucket to the condenser. Also, as stated earlier, the leaving velocity from the last stage bucket was high because of the overloaded last stage bucket.

Steam Path Deposits—As is typical for most geothermal steam turbines, the steam path of this turbine shows varying amounts of mineral deposits. The deposits are heaviest on the first stage, and diminish towards the exhaust. The deposits reduce efficiency by increasing surface roughness, changing the shape of the airfoils, and blocking flow area at the throats.

Design Improvements Made in the Uprate Design

Although designed primarily for reliable Naval propulsion service, the subject turbine was rather efficient for a turbine of this vintage. However, advances in steam turbine aerodynamic design since the 1940s were recommended to improve this turbine's efficiency. Figure 4 is a cross-section showing the uprated turbine design.

Only the components which gave the most gain were included in the uprate scope of supply, and the specific efficiency improvements made in each section of the turbine will now be described.

Inlet Flow Guide—An inlet flow guide was designed to prevent the incoming steam from expanding suddenly to fill the entire inlet plenum. The guide also accelerates and smoothly directs the flow into the first stage diaphragms. The flow guide extends the full 360° around the circumference of the first stage nozzles, and is mechanically attached to the diaphragm inner ring, as shown in Figure 5. An additional efficiency improvement was obtained when the unused disks were machined from the rotor to eliminate the windage loss that they caused. It is esti-

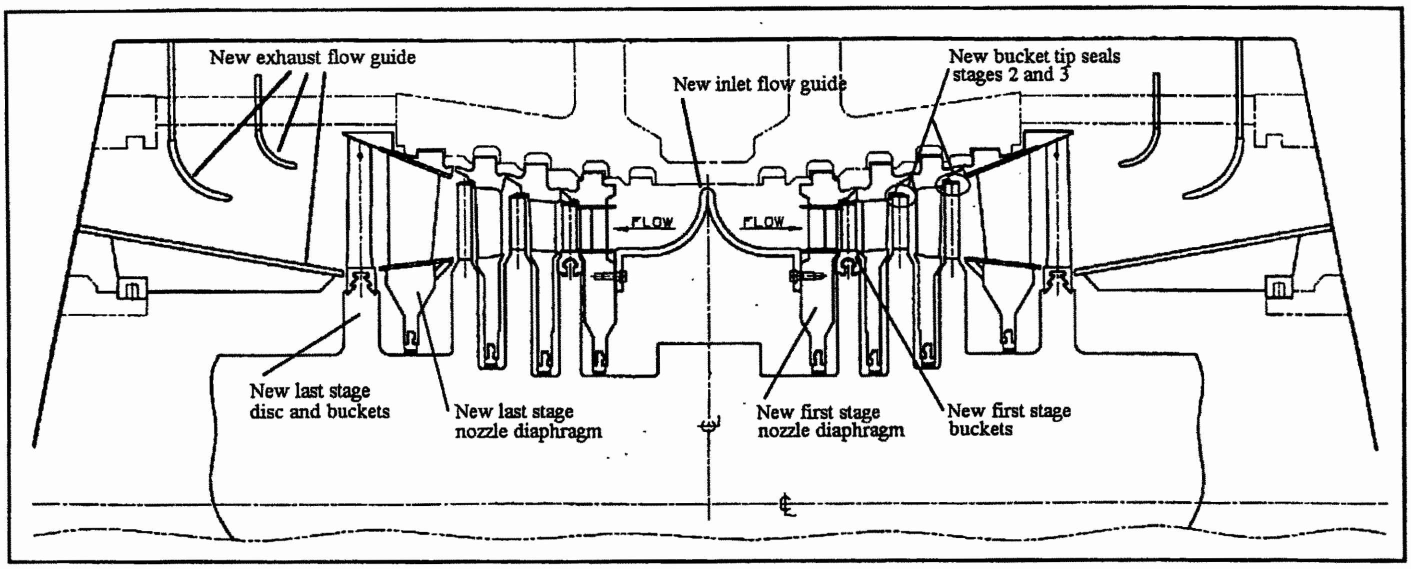

Figure 4. Uprated turbine design.

mated that the modifications made to the inlet area provided about 0.5 to 1.0 % of overall turbine efficiency improvement.

New High-Efficiency Blading—The efficiency of a steam turbine is determined in large part by the aerodynamic design (i.e. the airfoil shape) of the nozzles and buckets. In most uprate opportunities the greatest performance improvement potential lies in the replacement of older style blading with modern designs using advanced airfoil shapes.

The existing first stage (both nozzles and buckets) was replaced by a new Elliott high efficiency stage. The new nozzle area was also increased to improve flow passing capacity, and

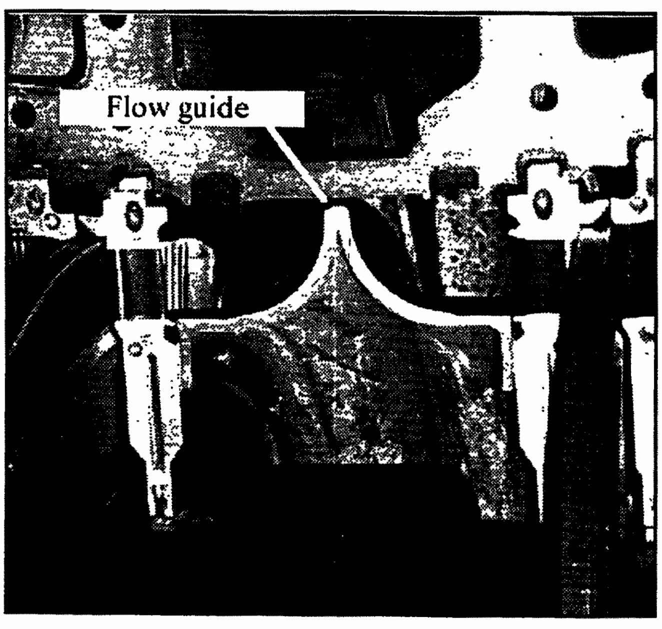

Figure 5. Inlet flow guide.

better distribute available energy over the steam path to maximize the efficiency of the stages. The replacement stage design includes a nozzle diaphragm that incorporates high aspect ratio nozzle blades spaced between high strength support nozzles. See Figure 6.

This particular stage design belongs to a family of HP/IP buckets developed by Elliott Co. and incorporates new airfoils designed to yield superior aerodynamic performance. Figure 7 shows the Mach number distribution plot for the new HP/IP bucket design with the new bucket profile superimposed on the chart for reference. Figures 3 and 7 can be directly compared to see the improvements achieved in the new airfoil design. Note the smooth shape of the suction side velocity distribution. The abrupt acceleration and deceleration of the flow seen on the early design has been eliminated by the new airfoil shape which provides a more controlled diffusion towards the trailing edge of the bucket flow path. For more information about the new Elliott blading, see references 1 and 2.

Significant efficiency gains are achieved when replacing old designs with new designs. In this case, the new airfoil designs result in an efficiency gain of between 4.0 and 5.0% per stage.

The new first stage buckets were specifically designed to reuse the existing root form to avoid expensive modifications to the disk. The mechanical design of the new bucket was analyzed extensively to confirm that the new airfoil would be compatible with the existing root design. A new nozzle diaphragm was fabricated which would be installed into the existing first stage casing groove.

Addition of Tip Seals—The new first stage design includes a bucket tip seal to reduce leakage, however, the existing second and third stages needed to be modified to add a tip seal. An extension ring was welded to the outer ring of the existing second and third stage diaphragms, then machined to control clearances

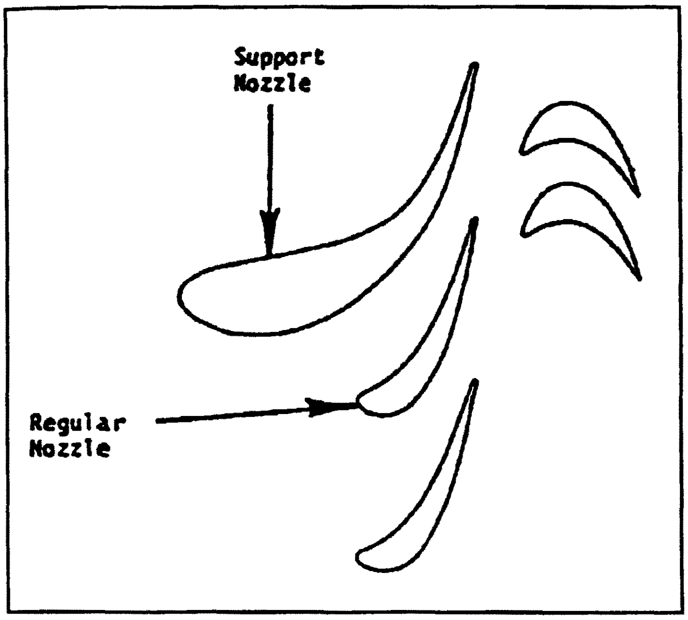

Figure 6. New high efficiency stage design.

for a new tip seal installed in each stage. A land was machined into the bucket shroud to ensure that a tight seal clearance is maintained when the turbine rotor moves in the axial direction during operation. The addition of tip seals was calculated to add approximately 2.0% efficiency on each of the second and third stages of the Brady Power LP turbine. Figure 8 shows the new tip seal geometry.

New Larger Last Stage—A new last stage was specially designed for this turbine which incorporated more flow area by increasing the height of the blades, and opening the nozzle and bucket exit angles. This had the effect of unloading the last stage by shifting more thermodynamic energy drop to the stage immediately upstream of it. The stage immediately upstream of the last stage operates at higher efficiency levels because it experiences lower moisture levels than the last stage. The transfer of available energy from the less efficient last stage to the more efficient preceding stage contributes to the improvement of the overall turbine's performance.

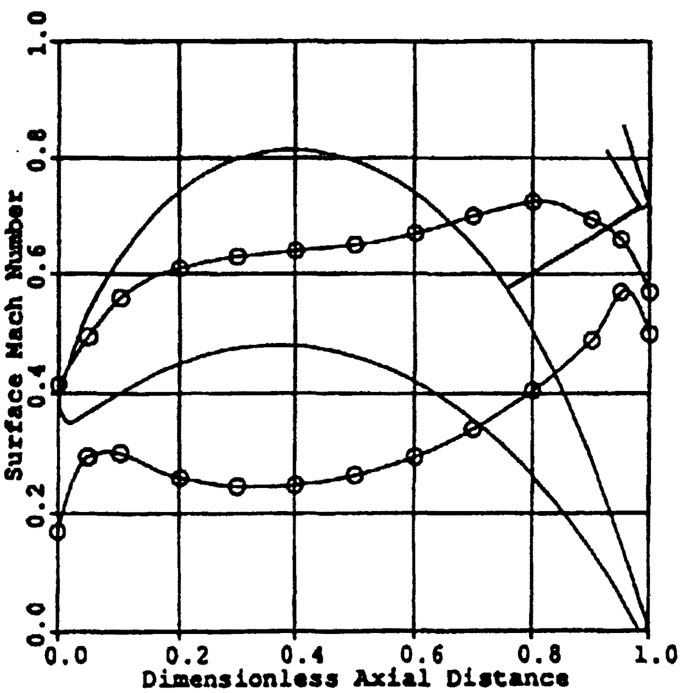

Figure 7. Mach number distribution of the new elliott high efficiency design.

The existing inner casing diameter limited the maximum possible height of the new last stage bucket. It was decided that on-site machining of the turbine casing would be too expensive (and time consuming), so instead, the axial location of the last stage disk on the rotor had to be moved downstream beyond the end of the inner casing. Moving the stage downstream 3.0 inches allowed the new bucket height to be large enough to maximize the uprated performance. The existing last stage disk was machined from the rotor in both flow directions. An entirely new disk was built up on the rotor shaft using an Elliott-proprietary rotor welding process. The resulting disks were finish machined to accept the new high efficiency last stage buckets.

To accommodate the larger last stage bucket height, a new nozzle diaphragm was also manufactured. Like the new first stage diaphragm, the mounting and alignment hardware for the new last stage diaphragm was designed to be compatible with the existing GE casing design.

Exhaust Hood Improvements—Any improvements made to the exhaust hood of a steam turbine will directly increase the available energy over the latter stages, especially the last stage. Because the subject turbine has only 4 stages, any improvements in the last stage performance will have a great effect on overall turbine efficiency. The first modification done to the exhaust was to remove the unused astern casing element. This opened the flow area considerably.

Next, a set of custom-designed exhaust guide vanes were designed to match the flow distribution coming out of the new last

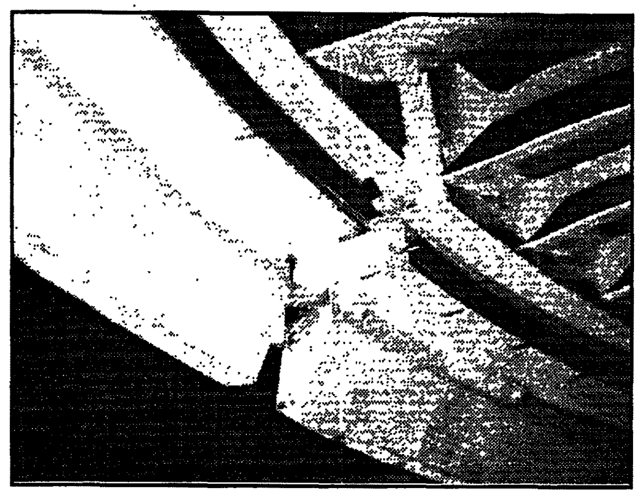

Figure 8. Tip seal addition.

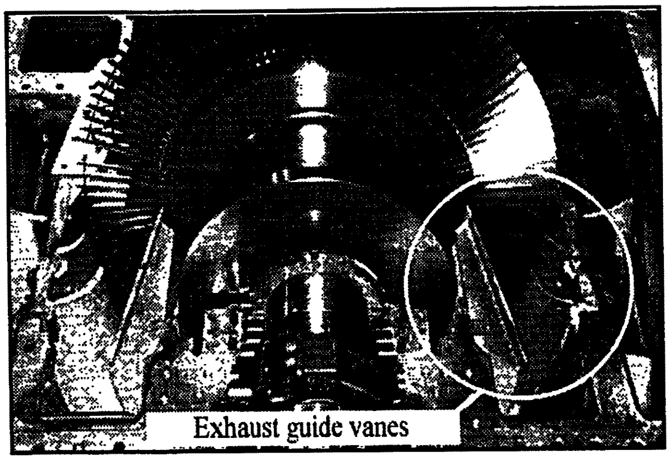

Figure 9. New last stage and exhaust low guides.

stage bucket. Figure 9 below shows the installed exhaust guide vanes. The purpose of these guide vanes is to help maintain an even distribution of steam flow over the entire exhaust hood, thus, preventing localized regions of high-velocity flow. Because pressure loss is proportional to velocity squared, it is important to reduce high velocities wherever possible in the exhaust flow. The guide vanes effectively act to split up the flow leaving the last stage bucket, and divert flow to areas in the exhaust hood that would otherwise be stagnant. As a result, more of the existing hood area is being utilized, and the exhaust velocities are more evenly distributed. It was calculated that the exhaust hood improvements reduced the pressure at the exit of the last stage bucket by approximately 20%, which means about that same percentage output increase on the stage.

Coatings on Steam Path— For the purposes of anti-fouling and corrosion resistance, a coating system was applied to the rotor and all nozzle diaphragms. The coating is comprised of inorganic aluminum pigmented base coats and a Teflon-based top coat. The top layer of the coating has a low coefficient of friction and is intended to resist the buildup of mineral deposits to maintain the efficiency of the steam path. The base layers of the coating are intended to provide sacrificial corrosion protection against the aggressive chemical environment present in the geothermal steam turbine.

Field Installation and Performance Testing

Part of the uprate workscope included a pre- and post- uprate performance test. It was agreed between Elliott ATS and BPP that in order to accurately confirm the efficiency improvement from the uprate, the *difference* in output would be measured from identical tests conducted before and after the uprate. Therefore, the difficulty of measuring absolute efficiency would be avoided.

The uprate outage began a few days before the new hardware arrived at the BPP plant. The pre-uprate performance test was completed. Great care was taken during the course of the outage on-site work to prevent any damage or adjustment of the instrumentation. The intention was to prevent any instrumentation bias between the pre- and post- uprate test by not changing any of the instruments or their settings.

The new and refurbished hardware was delivered to the BPP plant during the outage. One assumption agreed to between Elliott ATS and BPP during the design and manufacture of the uprate was that the LP casing in operation was identical to the spare casing used to trial fit the new hardware. During the outage it was discovered that there were, however, slight differences between the two casings, and some final fitting of the new nozzle diaphragms in the casing grooves was required. A spacer ring was also needed between the inlet flow guide and the first stage nozzle diaphragms. In addition, when the rotor was installed into the lower half casing, the last stage tip clearance was too small on one end of the double flow rotor. This situation was corrected by performing a tip grind on the affected last stage bucket row (with the rotor in place in the lower half casing).

The exhaust guide vanes were welded directly to struts in the exhaust hood per design. Care was taken to assure that distortion was not caused by excess welding.

After all hardware was installed, and the unit brought back on line, the post-uprate performance test was completed. See reference 3 for more information about the performance testing. The uprate modifications to the turbine caused the inlet pressure to be somewhat reduced because of flow capacity increase. The deviation from the intended test conditions were easily overcome by the use of Elliott-provided performance correction curves and flow capacity corrections.

The corrected uprated turbine performance showed an output improvement of 675 kW. The efficiency and output improvement guarantees were fully met.

Conclusions

The performance of a geothermal steam turbine has been cost effectively uprated by a non-OEM through the use of advanced technology aftermarket techniques:

- The existing turbine was analyzed and performance modeled to confirm uprate benefits.
- Cost-effectiveness was achieved by identifying and uprating only the components which gave the most efficiency gain, including:
  - * inlet flow guide
  - * new first stage nozzle diaphragm and buckets
  - * bucket tip seals on existing second and third stage nozzle diaphragms
  - * new last stage nozzle diaphragm and buckets
  - * exhaust flow guides
  - * coating of rotor and diaphragms

- The calculated efficiency improvement was confirmed by field performance tests.

References

Perera, J.V. 1990. "Steam Turbine Performance Gains from Improved Blade Designs," Advances in Steam Turbine Technology for Power Generation, *PWR*, vol. 10, October.

Perera, J.V. 1992. "Redesigned Turbine Blading and Steam Path Optimization for Higher Efficiency," *Steam and Combustion Turbine Blading Conference*, EPRI, January.

Overby, F.R., 1996. "Brady Geothermal LP Retrofit Results," Florida Power & Light interoffice correspondence, November.