Turbine Modernization Projects at Susquehanna and Salem Nuclear Plants Maximize Performance at Current and Future Uprate Steam Conditions

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TURBINE MODERNIZATION PROJECTS AT SUSQUEHANNA AND SALEM NUCLEAR PLANTS MAXIMIZE PERFORMANCE AT CURRENT AND FUTURE UPRATE STEAM CONDITIONS

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Abstract

The Susquehanna and Salem Nuclear Plants recently completed major turbine modernization projects that maximized output and addressed goals such as life and license extension, reliability issues, and optimizing the turbine steam paths to the uprated steam conditions.

The Susquehanna Steam Electric Station (SSES), a boiling water reactor nuclear plant, upgraded the HP and three LP steam turbines on both its units to maximize performance and address reliability concerns. During the first four years of its commercial operation, Susquehanna experienced problems with disc-cracking on the LP turbine rotors, which was addressed by replacement in-kind monoblock rotors. Although the plant resolved the disc-cracking problem, subsequent problems developed with both dovetail cracking and inner casing erosion. In 2000, a SSES evaluation team recommended replacement of the steam path to address potential maintenance issues, maximize turbine performance through the application of the latest technology, and support planned reactor thermal uprates.

The Salem Nuclear Plant evaluated similar long term issues and decided to modernize their turbine steam paths to improve performance and optimize their output with flexibility for future steam generator replacement. This involved two HP replacements and three new LPs on both units.

Both of these projects utilized a full arc reaction high pressure turbine and an advanced disc design low pressure turbine replacement. This paper will present to the industry the key aspects of these two leading edge projects, which includes provisions for future turbine modifications in at both plants that will further uprate and optimize the steam path to future steam conditions.

Susquehanna Project

The SSES main criteria for the replacement turbine steam path were performance improvement, proven technology and reliability. As part of the technology aspect, the Susquehanna Team also required that proper material selection/composition /placement on the new LP turbines also be a major evaluation characteristic.

The author's company was awarded the turbine modernization project on January 23, 2001 to replace the LP turbines as well as the HP turbine of both Units 1 and 2 at SSES. The HP turbine replacement was justified due to the need to optimize the turbine to 1.4% uprated flow conditions and the additional MWe output provided by replacing this element. Susquehanna Unit #2 was installed first in March 2003 followed by the Susquehanna Unit #1 installation one year later in March 2004. Both installation outages were completed in 38-days.

After pre-and-post performance testing conducted in accordance with ASME PTC 6.1, the performance improvement results show more than 80 MWe improvement per unit, with around 50 MWe attributed to the new turbine technology per unit.

The Susquehanna Nuclear Plant is not finished uprating their station output. As part of plant output maximization initiatives, there are future plans to increase reactor thermal flow an additional 13 % in the near future. To support this initiative, an order was recently issued for new HP turbines that will replace the ones installed in 2003 and 2004. The sole purpose being to maximize output and re-optimize the turbine after the steam uprate planned in 2007 and

2008. The supplier and customer worked together to maximize the MWe plant output taking into account the backpressure impacts on the LPs and generator output capability.

Salem 1 & 2 Project

The Salem 1 and 2 Modernization Project focused on improved thermal performance, operation flexibility, and long term reliability. The work scope consisted of replacing the entire steam path (HPT and three LPTs) for Salem 1 and only the HPT element on Salem 2, since LPTs were replaced already in 1996 with OEM provided monoblock rotors. The replacement LPTs for Salem 1 are the Advanced Disc Design technology. that impacted the original schedule. Turning gear was restored on May 14, 2004 or 10 days over plan. Unit 1 was synchronized on June 3, 2004 and performance testing completed the week of July 5, 2004.

Salem 1

The outage began on March 30, 2004. Since Salem is an outdoor plant, there were weather problems that resulted in outage delays. Also, additional repair work on the HP outer cylinder was emergent work

The performance output guarantee for Unit 1 was exceeded. Measured performance improvement attributed to turbine technology only was 45 MWe and the project termed a success for all stakeholders.

Salem 2

Salem 2 work scope consisted of only a replacement HPT steam path. The outage started on October 9th, 2004 and the required modification to the HP outer casing was performed according to schedule. Turning gear was restored on November 19th, 2004, synchronized on November 29th, 2004 and performance testing completed the week of March 18th, 2004.

Additionally, Salem 2 is planning to increase steam generator pressure in 2008 with the replacement of their steam generators. In anticipation of this change, the replacement HP turbine was designed with “convertibility” features. Essentially, blade spacing and root geometry were designed into the unit to support a future change of the inlet admission ring and the first drum stages. This will allow the future “converted” HPT steam path to reuse the rotor and stationary components and require only minimal equipment change-out at the future increased steam pressure. Figure 1 shows the retained and replaced components for the HP Hybrid Turbine Concept. This work will re-optimize the steam path to steam generator output conditions and maintain the optimized efficiency output point.

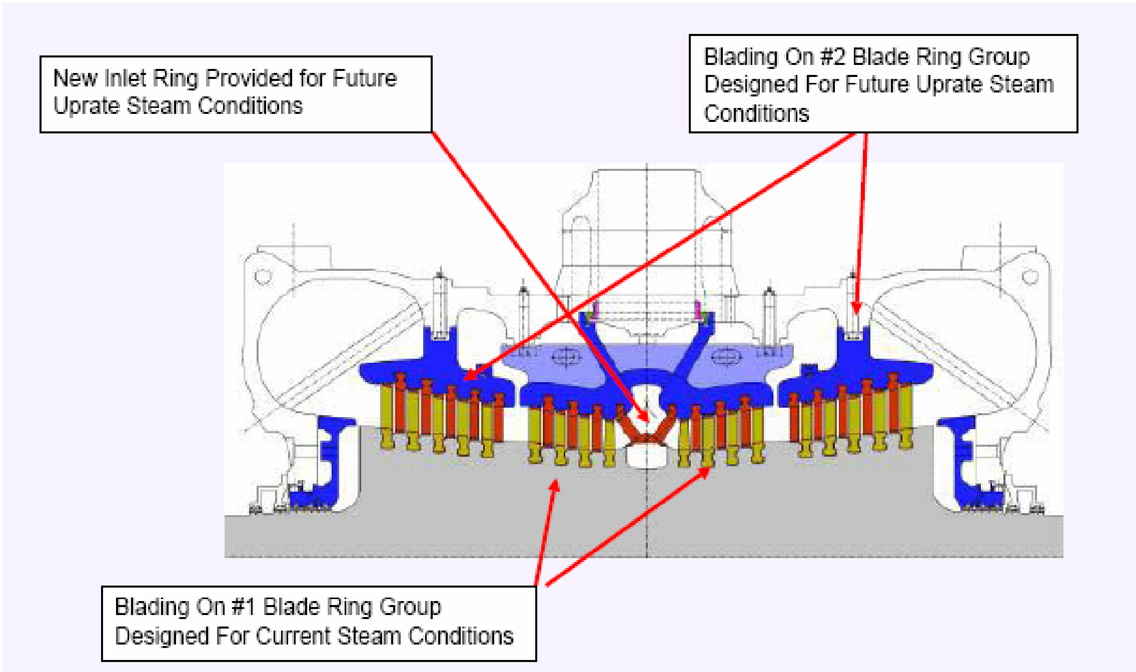

Figure 1: High Pressure Hybrid Concept

On base-loaded nuclear steam turbines, the full arc reaction high pressure turbine has a proven record of offering the maximum output and efficiency at design conditions. This design has been used on OEM and non-OEM applications successfully on over 26 modernized units.

Existing Turbine Reliability Issues

Susquehanna

The original turbines at Susquehanna Steam Electric Station (SSES) had a history of disc inside diameter cracking in the keyway areas which was the driving factor to change the LPs.[1] Such disc cracking is a well-known problem in the industry caused by stress corrosion on some shrunk-on disc designs as well as fossil units as well. The Advanced Disc Design LP Rotors (see Figure 2) and its earlier versions fortunately never shared these generic SCC issues due to precise keyway design and material treatments. This has been supported by numerous inspection results and technical papers on this topic.[2]

Additional concerns on the LP turbine reliability were dovetail cracking and inner casing erosion. The dovetail cracking is stress corrosion cracking that occurs in the attachment root for the turbine blades and was a potential issue on the SSES LP rotors. Casing erosion was also a serious long-term reliability issue on the original LP turbines at SSES since these are non-reheat turbine units.

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[2] David, W., Roettger, G., Schleitthof, K., Hamel, H., Termuehlen, H. “Disk-type LP Turbine Rotor Performance“, International Joint Power Generation Conference, Kansas City, MO 1993.

Susquehanna maintenance personnel had to monitor and repair severe erosion on the original design LP turbine rotors and inner casings.

Although there were no long-term maintenance reasons to retrofit the HP turbines, a decision was made to proceed with their retrofit because the increased MWe justified their replacement.

Salem

At the Salem Plant, the owner was also committed to addressing the long term reliability issues of the turbine. Salem 2 had already replaced the LP turbines in 1996 with OEM Westinghouse monblock LPTs and further replacement was not justified.

In order to focus on the long term solution, the decision was to replace the LPs on Salem 1 as well. In this case, the rotors were the Advanced Disc Design.

Salem Unit 2 is planning a steam generator replacement for 2008. This required some unique design compromises to be built into the replacement HPT in order to allow it to be modified for the future conditions and be optimized for the best electrical output at both operating steam conditions. A “Hybrid HPT” provided this flexibility.

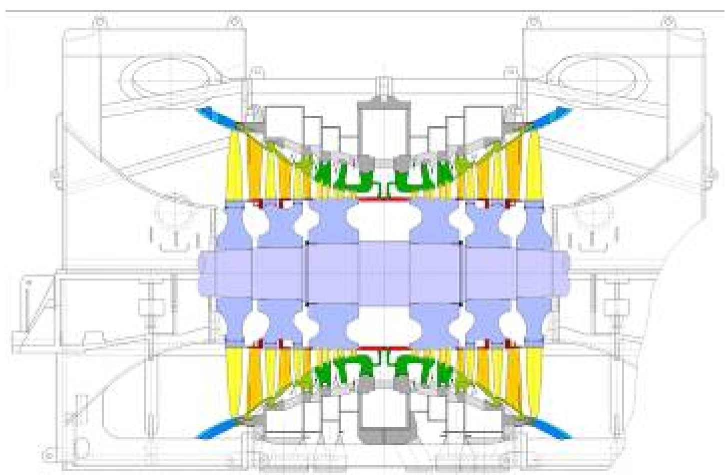

Figure 2 – Typical Advanced Disc Design LP Turbine

Figure 4 – LP Rotor Staged at SSES

PSEG-Salem System Overview

During the Turbine Retrofit Project, Salem Plant also replaced their old Turbine Electro-Hydraulic Control (EHC) Systems on both units. The original EHC System represented technology that was over 25 years old and it was becoming increasingly difficult to maintain this system. After detailed discussions to better define the work scope and understand the owner's needs, a separate I&C team took ownership of this significant sub-project to the main turbine project. The Woodward MicroNet™ Digital Control System was selected based on the owner's preference and the proven 400 installations of this system

The new turbine control system components consist of a MicroNet™ digital control main chassis, a MicroNet™ power supply chassis, and redundant auxiliary power supplies all contained within an electrical Equipto enclosure.

The MicroNet™ digital control system is designed to be fault tolerant through redundant CPUs and I/O channels. The main chassis contains three kernels, "A", "B", and "C". The separate power supply chassis provides redundant power inputs to each of the independent kernel sections of the main chassis. In addition, each kernel has its own power supply, CPU, and four I/O slots.

Kernels A and C contain a power supply, a CPU, an Ethernet module, an analog/speed sensing combo module, a high-density discrete input/output module, and an actuator output driver module. Kernel B consists of a power supply, a CPU, an analog/speed sensing combo module, a high-density discrete input/output module, and two actuator output driver modules.

An Engineering Workstation is provided near the turbine control system cabinets in the Electrical Equipment Room. This workstation provides indication of system parameters (both internal and external), maintenance functions including testing, calibration, and programming. Additionally, a laptop computer is provided for remote use (at turbine) by maintenance personnel for calibration of valves.

The Salem operators report that the system is extremely user friendly and a great asset to the operations of the plant.

Proven Technology and Reliability

The Advanced Disc Design Low Pressure Turbine design was installed for both the Susquehanna and Salem LP turbines and they essentially share most of the same design features.

Advanced Disc Rotor and Turbine Design Highlights

The retrofit LP design completely replaces the original rotors and inner casings, with minor structural modifications to the LP exhaust hoods. For both the Susquehanna and Salem applications, the 13m^2 LP turbine design was provided, which refers to the approximate exhaust area of each LP flow. The retrofit turbines will be designed to fit into the existing turbine bearings and operate with all the existing auxiliary systems.

This advanced disc design LP rotor is the author's company's standard product offering for large nuclear LP turbine retrofits. See Figure 3 below showing the Susquehanna rotor.

Figure 3 – LP Rotor Staged at SSES

Main LP Turbine Design Features

Other noteworthy design features that were incorporated into the LP turbine design are summarized as follows:

- Free standing LP rotating section blades (3 stages per flow) with 46-inch last stage blades.
- Flame hardened leading edges of the LP freestanding rotating blades to mitigate moisture erosion.
- Forward leaning last stage stationary blades for improved last stage rotating stage flow distribution.
- Moisture removal slots in the last stage stationary blade ring to reduce moisture erosion.

- Optional Boroscopic inspection ports in the inner casing, to allow for blade inspection without casing disassembly.
- Integrally shrouded stationary and rotating drum stages.

In addition, inter-stage sealing is accomplished with “fin-fin” or “look-thru” style seal strip arrangements that allow for greater axial displacements. See figure 4.

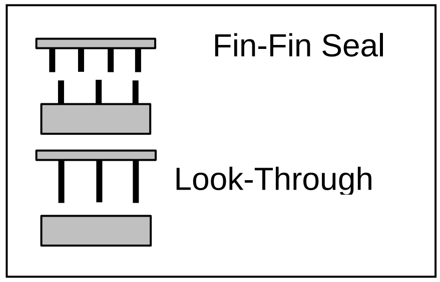

Figure 4 – LP Seal Arrangements

Features that contributed to the increased performance improvement are:

- Ability to use larger back-end blading of 46-inch length.
- Flexibility to increase number of blade stages.
- Optimized turbine design for the available steam conditions or uprate.

Surface Stress Management to Avoid Stress Corrosion Cracking (SCC)

In addition to careful selection of materials and strength levels, several techniques are used to further enhance resistance to SCC:

- All of the LP discs receive special heat treatment to impart residual compressive stress on the disc surfaces.
- Disc 1 (innermost) is shot peened on its side surfaces and in areas of the blade grooves and entering slots. Keyways, located only on this first disc, which are in fact cylindrical for pin insertion, are bored, rolled, and honed.
- Disc 2 is shot peened on its side surfaces and in the caulking piece grooves.
- Disc 3 has no additional shot peening, but the last row of rotating blade roots are rolled.

The above SCC mitigation features were evaluated in 1995 by an independent consultant prior to award of a major turbine retrofit project.[3] This independent review supported claims that the “Advanced Disc Design addresses those areas in other manufacturer’s designs that have led to early retirement of those rotors due to SCC in their shrunk-on discs. Additionally this report cites that the “Advanced Disc Design stress concentrations are low compared to similar stresses which we have calculated for other manufacturer’s designs in equivalent areas. The lower stress states combined with the manufacturing procedure which results in residual

[3] MPR Associates Inc Report (Proprietary) titled “Limerick LP Turbine Replacement Rotor Proposed by Siemens Power Corporation Evaluation of Margin with Respect to Disc SCC”, December 1995.

compressive stresses in the periphery of the disc should provide good resistance to SCC in the attachment area."

There has been much debate in the industry concerning the most effective LP turbine rotor design against SCC formation. Most turbine manufacturers originally manufactured disc-type LP rotors for nuclear power plants due to the available manufacturing technology and the large sizes of forgings required for these mostly half-speed turbines. After industry-wide SCC issues developed in some OEM designs, which was mainly in the disc keyway areas, the affected OEMs turned to non shrunk-on disc designs (mono-block and welded construction) as the obvious solution. The author's company however, never had these generic SCC problems on its shrunk-on LP rotor design. This has been verified independently, as discussed in the preceding paragraph, as well as in a number of technical papers by the author's company.[4]

LP Inner Casing Replacement

One of the most common approaches on a LP turbine modernization is to replace the inner casing to correct for any casing erosion damage and also to allow greater flexibility to design the optimal blade path to improve performance. This typically necessitates larger blade lengths that make the reuse of the inner casing very difficult. Figure 5 below shows the most common approach, namely the LP rotor and inner casing replacement shown here with all internals in place and ready to install the upper casing half.

Additionally, a situation more specific to BWR plants without reheat, is inner casing erosion problems. Some of these plants have requested that the composition of the inner casing materials be upgraded from the common carbon steel construction in high flow areas in order to prevent future casing erosion issues. Such requests are best handled on a case by case basis in order not to "over engineer" the replacement casing.

Installation Scope and Duration

In general, the LP turbine retrofit requires cutting and re-welding of all inlet and extraction piping, in addition to the installation and alignment of the new turbine components. On BWR units, such as Susquehanna, the presence of radioactive contamination and health physics issues present additional challenges for the installation team.

The HP turbines retrofit required specialty machining to modify and reuse the original outer casing. The main modification work involved converting the existing high pressure turbines from a partial arc to a full arc reaction machine.

Susquehanna

At a BWR Plant, the replacement of the entire turbine train during a 38-day outage was unheard of just a few years ago. This is possible with an entire LP casing change-out due to the following:

- Reduced risk of encountering components that require repair, which would increase outage critical path.
- LP turbine lower-half components can be pre-aligned and installed as a single unit/lift.

[4] David, W., et al. 1993.

- Dedicated and experienced (owner and vendor) project teams that are committed to thorough and rigorous pre-planning.

Figure 5 – Salem 1 LP Turbine with Rotor and 1st upper blade ring installed

Maintenance Benefits

This LP rotor design has already been approved by the NRC for disc inspection intervals at 100,000 operating hours.[5] From an engineering standpoint, the remaining stationary components are also approved for maintenance intervals up to 100,000 operating hours, which is typically over 12 calendar years.

Reducing the frequency of control valve testing often results in operating cost savings. A majority of turbine vendors can offer turbine equipment that requires only quarterly valve testing. The full arc admission design HP turbines support such a testing regimen, while requiring less power reduction due to the full arc all reaction design, as compared to partial arc and impulse designs.

The main points of an LP casing retrofit that contribute to the reliability and extended maintenance intervals are:

1. Entire steam path is replaced which minimizes/eliminates the need for repairs in the future.
2. Existing original LP casings at SSES and Salem represented 20+ year old technology where issues are increasing, e.g. steam wash, erosion, etc.
3. Entire turbine is ready for 40+ years service life that fits into license extension plans.
4. Proactive approach to eliminate future concerns, which are a real possibility with reuse of existing LPT components.
5. Design is for 100,000 equivalent operating hour (EOH) inspection intervals/10 year approval from the Nuclear Regulatory Commission.

[5] Draft Safety Evaluation by the Office of Nuclear Reactor Regulation Technical Report No. CT-27332, Rev. 2, US Nuclear Regulatory Commission, February 10, 2004.

Figure 6 – LP Turbine Installation at SSES

High Pressure (HP) Turbine Design Highlights

As mentioned earlier, the HP turbine was retrofitted for the performance improvement benefit. Some of the design highlights of the HP turbine include:

- Mono-block design without through-bore.
- Stainless steel inner casing and blade carriers in existing outer casing, bearings, flow guide, etc.
- Inlet "L" seal design, providing sealing between the inner and outer casing. See Figure 8 below.
- Single piece high efficient inlet admission ring.
- Full reaction blade path.
- Advanced blade designs using "3DS" blading.
- Five strip inter-stage seals.
- Existing seven blade stage design will be replaced with 12 blade stages per flow.

In short, the HP turbine design requires conversion of the original nozzle chamber design to a full-arc all reaction blading design that is the most efficient design for large base load application. Through removal of the nozzle chamber from the old HP outer casing, sufficient axial space is gained to install a highly efficient inlet admission ring of full arc design and allow for additional reaction blade stages in the steam path.

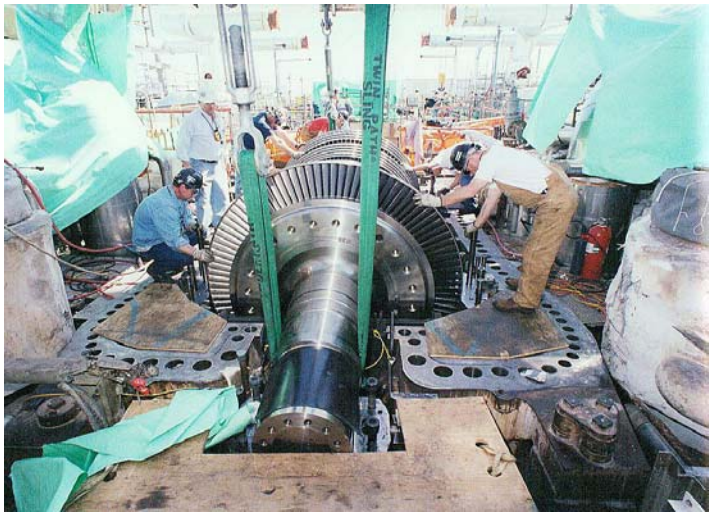

Figure 7 – HPT Installation at Salem

Future Uprate Plans and Approaches

Both the Salem and Susquehanna Nuclear Plants have focused on maximizing performance output of their nuclear assets through replacement turbine components that match their steam conditions.

Susquehanna already has stretched power uprate plans by increasing thermal flow up to 13% above current values. This program will maximize the electrical output from the generator without exceeding the capabilities of the new LP turbines.

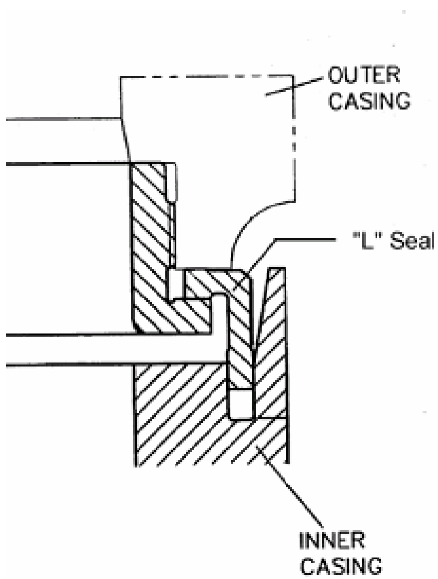

Figure 8 – L Seal Arrangement

As mentioned before, as part of this stretch increase, the owner has already committed for new high pressure turbines of similar design but matched to the new uprate steam conditions.

At the Salem Plant, Unit 1 is currently designed and optimized for the operating steam conditions. Salem 2 will increase their steam generator pressure in 2008, which will require the modifications to be made to the new HP rotor and stationary components as was discussed under the hybrid concept. The incremental cost of this “hybrid” work is a fraction of benefits achieved through having the HPT optimized at both the pre- and post steam generator pressure increase phases.

Conclusions

Both of turbine modernization projects performed at the Salem and Susquehanna Nuclear Plants are examples of their owners focus on maximizing plant output through thermal uprates and equipment upgrades optimized to the steam conditions.

Both the Salem and Susquehanna projects main characteristics and benefits of modernization projects are that they provide:

- Reduced Maintenance Costs from having new components
- Increased Capacity, Efficiency, and the Associated Revenues Increase through application of turbine technology in the following areas:
- Improved inter-stage shaft sealing
- Application of latest design 3-dimensionally shaped drum blades
- Improved blade profiles
- Shape of Last Stage (L-0)
- Size of the new last stage or larger exhaust annulus area
- Improved Availability and Reliability
- “Environmentally Friendly” Megawatts
- Short Payback period of less than 5 year (simple payback)

The solutions discussed, such as the hybrid HPT or an entirely new HPT that are specifically designed for a nuclear plants steam conditions, in tandem with latest technology LP turbines ensure that the turbine steam path is optimized and maximum electrical output is achieved.

[1] Power Gen 2001 Paper “Susquehanna Steam Electric Station Turbine Retrofit/Generation Uprate: Decision Factors For Long Term Reliability and Improved Performance

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