TECHNICAL PAPER

Title: **Matching Steam Turbines with the New Generation of Gas Turbines**

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Matching Steam Turbines with the New Generation of Gas Turbines

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1.0 INTRODUCTION

To meet the requirements of the highly competitive combined cycle (CC) power plant market, steam turbines (STs) have had to follow the same evolutionary path as heavy-duty gas turbines (GTs). These two types of equipment have become even more interdependent with the introduction of the new “G” and “H” GT technology classes. These new classes have created an inseparable thermodynamic and physical link between the primary and secondary power generation systems by using steam, instead of air, in a closed loop to perform most if not all of the GT cooling duty. The previous generation of GTs, the “F” class, has also undergone extensive modifications and upgrades. In addition to producing higher output, the “F” class machines are producing substantially more exhaust energy for the bottoming steam cycle.

This paper describes Bechtel’s experience with modern STs in all phases of a CC project: from the initial selection through construction, startup, and testing. The STs include all the major manufacturers, such as Alstom, GE, Mitsubishi, Siemens Westinghouse, and Toshiba, in several CC configurations.

The paper presents several CC projects that have been completed or are in advanced stages of construction. These projects employ the new generation of GTs and STs.

2.0 CYCLE SELECTION AND OPTIMIZATION

In the last 10 years, STs in CC applications have had to evolve significantly, from small 80 MW dual admission nonreheat configurations to multiple-pressure-admission reheat turbines with outputs reaching the 350 MW range. Because of this rapid evolution, many original small turbine designs have had to be modified or adjusted to compete in performance and capacity.

Significant basic differences exist between STs designed for CCs and conventional Rankine cycle (RC) applications. First, feedwater heaters are not normally used in the thermal design of the bottoming cycle for a CC; therefore, exhaust flows are much higher. Secondly, the steam is added to the steam path flow at several pressures from the heat recovery steam generator (HRSG) to allow the maximum amount of heat to be extracted from the GT exhaust energy. The CC low pressure (LP) exhaust steam flow, when compared with RC LP steam flow, can be up to 35 percent greater than the main steam flow. Thirdly, CC designs may use supplemental or duct firing in the HRSGs to compensate for the GT’s reduced output at high ambient temperatures, which coincides with maximum summer demand for power. In the U.S., it has become quite common to almost double the ST output by using massive amounts of supplementary firing to capitalize on peak summer demand. Finally, competitive market pressures have pushed the ST suppliers to offer a compact plant layout with axial steam exhaust using only two standard cylinders, thus reducing the cost of manufacturing and installation as well as length of the erection schedule (Ref 1).

Although a modular building block system with standardized components and turbine parts is typically employed by all ST manufacturers, it must be remembered that the steam blade path is individually designed for each application to achieve high efficiency. Even small blade path improvements can translate into large operational savings.

Figure 1 shows the typical thermal efficiency values for three modules (high pressure [HP], intermediate pressure [IP], and LP) recorded in several recent projects for both unfired and fired cases. As the figure indicates, turbine cylinder efficiency in the range of 94 to 96 percent is not uncommon. In this analysis, the power output for the fired case, with main steam pressure at 131 bara (1,900 psia), was 55 to 65 percent higher than the unfired case, with the main steam pressure at 69 bara (1,000 psia). It should be noted that with sliding pressure operation, HP and IP module efficiency does not change significantly between the fired and unfired cases, indicating that ST operation at part load does not adversely affect the power plant heat rate. The LP module efficiency, however, does change significantly, since it is affected by the specific selection and sizing of the module and heat sink, which determine the ST operating backpressure.

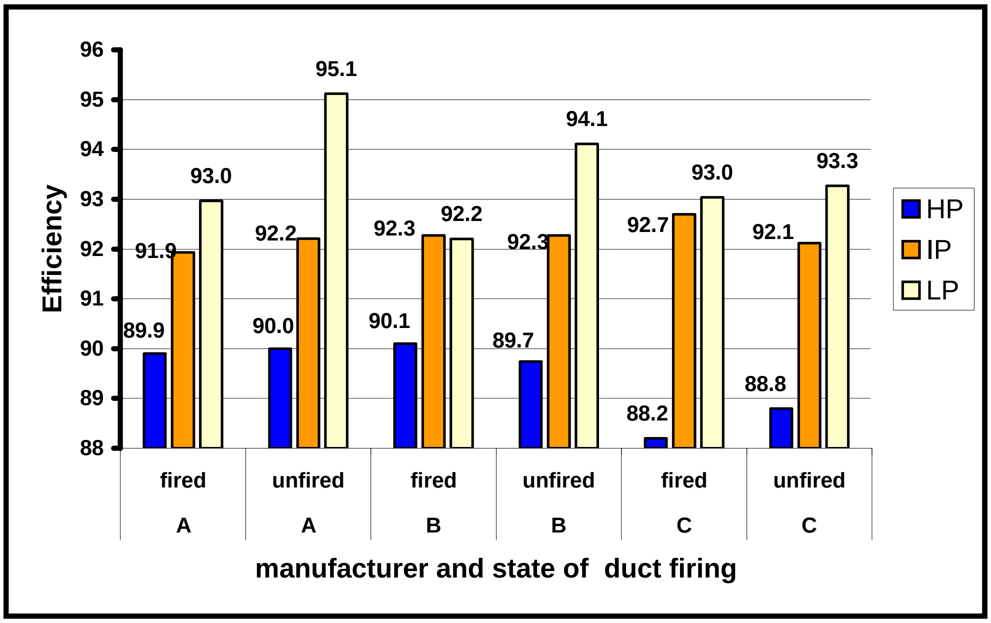

Figure 1. Steam Turbine Module Efficiencies for Duct-fired and Unfired Cases

3.0 PLANT CONFIGURATION SELECTION

One of the earliest tasks in the development phase is selection of plant configuration. Bechtel maintains a portfolio of standardized plant designs for each of the following configurations:

- 1 x 1 (one GT, one HRSG, and one ST)
- 2 x 1 (two GTs, two HRSGs, and one ST)
- 3 x 1 (three GTs, three HRSGs, and one ST)

This approach allows the EPC contractor to build a plant that best suits the owner's operating goals. A single ST for multiple GTs is less costly than a separate ST for each GT. However, multiple 1 x 1 configuration trains offer some significant advantages, as outlined below.

- *Phased construction flexibility*. Owners can add units as dictated by market conditions.
- *Speed to market*. As the construction duration of a 1 x 1 configuration is shorter than a 3 x 1 configuration, the first train can be brought on line more quickly and start generating revenues, while the remaining units are still undergoing construction.
- *Closer matching with dispatch demand*. A site with multiple 1 x 1 trains using supplemental duct firing can better and more efficiently match dispatch requirements.
- *Greater plant redundancy*. Each unit is completely redundant.
- *Optimized spare parts inventory*. Identical components are used for all trains.

4.0 EQUIPMENT SELECTION

Before selecting equipment from different suppliers, a thorough investigation is necessary to ensure that the owner's pro forma objectives are met for power output, heat rate, startup times, reliability and availability, etc.

The process includes an independent technology assessment of the equipment's operating history and quality control for the engineering and manufacturing processes. In addition, the performance offered by the original equipment manufacturers (OEMs) for a specific project is normalized and reconciled with past performance of the same equipment in a similar configuration, as achieved on other projects. Bechtel maintains a performance database of all past projects that is routinely updated with information from field tests.

Special consideration is given to cogeneration plants where selection of cycle pressures and locations of the steam extractions is limited by the commercial availability of STs that can meet the full range of specified conditions. Another decision needed on most cogeneration projects involves the ability to cold start the ST while the plant continues to supply full process steam requirements to the host. At the other extreme, it is also critical to determine whether to design the ST and associated steam cycle equipment for the maximum steam case when no steam is required for the process. In this scenario, a larger LP section and an increased capacity for downstream electrical equipment (transformer, isophase bus, etc.) are required. In making the selection, careful consideration should be given to economic benefits to be realized from the availability of the extra power and operational constraints due to possibly infrequent occurrences of such conditions (Ref 2). Equipment selection requires the unique expertise and value-added service that only an experienced EPC contractor can provide to the customer.

5.0 CORPORATE EXPERIENCE

Over the years, Bechtel has executed more than 96 projects using 170 GTs and more than 96 STs in CC applications. In the last 5 years alone, Bechtel has executed 25 projects, installing and starting up 58 GTs and 38 STs.

Table 1 lists STs from major suppliers that have been used in Bechtel CC projects around the globe. The following discussion is based on the experience gained in the design and commissioning of these projects.

Table 1. Steam Turbines from Major Suppliers

Supplier	No. of Units	Nominal Power (MW)	Characteristics	CC Configuration
Alstom	7	250		2 x 1
Alstom	12	85/155	Unfired/duct-fired	1 x 1
Alstom	1	300		3 x 1
GE	1	300		2 x 1
GE	2	250		3 x 1
GE	1	150		1 x 1
GE	1	120	Desalinization noncondensing unit	1 x 1

Supplier	No. of Units	Nominal Power (MW)	Characteristics	CC Configuration
GE	3	200		2 x 1
MHI	2	100	Cogen with large process steam	2 x 1
SWPC/MHI	1	120		1 x 1
SWPC	4	150		1 x 1
SWPC	1	295		3 x 1
Toshiba	1	300		3 x 1
Westinghouse	1	230		2 x 1
Total	**38**			

6.0 STEAM PATH OPTIMIZATION AND SECTIONS

While ST design is a mature technology, manufacturers continue to improve the output and efficiency of their equipment through improved blade designs and superior materials to accommodate higher main and reheat steam temperatures. Computational fluid dynamics (CFD) techniques coupled with rig and field tests have been extensively applied to develop three-dimensional blades, vanes, and passages. Competitive pressures to maintain a small footprint have also pushed new designs to focus on fundamental blade path parameters and offer increased stage count, reduced blade root diameter, and optimized reaction values to minimize leakages. Comparison of individual loss mechanisms can identify and correct the major contributors to losses such as valves, and nozzle and blade profiles (Ref 3).

As design performance has improved, margins have decreased, making ST performance more sensitive to detailed design issues such as surface finish and seal design.

7.0 EVALUATION OF THE EXHAUST SYSTEM: AXIAL, DOWNWARD, OR LATERAL

With the high LP flows associated with CC STs, greater emphasis is placed on the last-stage blade (LSB) dimensions and material. One of the major loss mechanisms in the ST is the kinetic energy of the steam as it leaves the LSBs—the lower the kinetic energy that can be achieved, the higher the resulting ST efficiency. The amount of loss is proportional to the ratio of the volumetric steam flow rate through the LSBs and the annular area of the turbine exit. To decrease this loss, a larger turbine exit annulus is required (Ref 4). Numerous challenges face designers, who must marry complex 3D aerodynamic designs with robust mechanical features in this erosion-prone environment. One typical example deals with aeroelastic instability, which is one of the more challenging design problems for very large LSBs. Aeroelastic instability is a vibration induced by flow, which occurs at off-design conditions in the regions of low axial steam flow and/or at high condenser pressures. The phenomenon can lead to flow separation from the airfoil, blade stall flutter, and buffeting of the blades. Some manufacturers have opted for titanium as the LSB material because of its high strength/weight ratio and superior corrosion resistance. However, titanium has reduced damping properties; therefore, it is generally necessary to change blade construction from freestanding to an interlocked design for increased mechanical stiffness. Despite numerous rig tests, theoretical analysis, and empirical data verification for new blades, designs with proven operational records at severe off-design conditions should be preferred.

The axial exhaust design is preferred because of its superior thermodynamic performance through lower pressure losses, greater pressure recovery in the diffuser, and simpler and less expensive construction. Because of the compact design and lower elevation, the capital cost of the ST and the associated turbine building can be reduced by 40 percent over using a double flow LP module with a bottom exhaust arrangement (Ref 1).

8.0 CONSTRUCTION

With the pursuit of compact, more efficient designs by ST manufacturers, construction tolerances and startup requirements have become more critical. As the capacity of CC STs has continued to grow, economic factors have pushed manufacturers to try to maintain the same cylinder sizes. These designs have resulted in reduced design margins and equipment that is much more sensitive to construction variables.

Reducing the number of bearings used to support the rotor in the turbine generator set allows for shorter overall length and lower costs. Use of fewer bearings results in higher bearing loadings and increased sensitivity to vibration, which in turn leads to additional startup delays due to the added balancing time.

With the axial configuration, the location of the outboard LP bearing is an additional concern. Normally, bearing housings are easily accessible from the outside, and the housing is maintained at atmospheric pressure or at a slightly negative pressure by the vapor extractors on the lube oil reservoir. With an axial design, this bearing is located within the exhaust region and is subject to condenser backpressure conditions. In some cases, a small amount of leakage across the housing flanges or inspection openings introduces oil into the cycle. Because this leakage is difficult to detect, the resulting cleanup can be extensive and time consuming.

The axial exhaust design has an additional feature that is sensitive to design tolerances—the large axial loads on the turbine during startup that are transmitted to the turbine foundations. The foundation is expected to handle this loading with minimal deflection, and the slide plates under the turbine are designed to freely allow the cylinder to grow. This large axial load, due to both differential and thermal pressure, results in varying amounts of deflections, and the variation in slide plate friction results in further variation. Further temperature stratification of the HP and IP cylinder due to differential warming or cooling during startup or shutdown has resulted in rotor binding if not adjusted properly. The sensitivity of the ST to these conditions results in further delays in project startup.

The conversion of standard 50 Hz designs to 60 Hz conditions has also resulted in unforeseen problems. Steam turbine sets that have had many reliable operating hours in their original 50 Hz configuration have caused a variety of startup delays. The most significant difficulty is the introduction of high vibrations that are transmitted through the STs and generators into the piping or foundations.

9.0 STARTUP

The ST startup flexibility and commissioning time play a significant role in startup of the entire CC plant. Heavy penalties for failing to bring the unit on line as scheduled mandate that predicted unit startup times be achieved. In addition, due to higher fuel costs and increased electrical reserve margins, CC plants are being dispatched as intermediate-duty units rather than base load, as originally envisioned. Achieving the goal of a fast and reliable startup requires careful design and integration of the ST and BOP requirements. On one hand, the ST supplier should provide more flexible ST startup parameters (such as greater steam temperature mismatch and more relaxed steam purity) while maintaining reasonable constant life consumption (Ref 5), controlling low cycle fatigue by monitoring the maximum wall temperature differences and permissible ramp rates. On the other hand, an EPC contractor can employ the entire arsenal of auxiliary equipment available to assist in providing the narrow preoperational and operating conditions that the modern ST requires (Ref 6) . Improving heat retention after shutdown, using advanced water treatment systems to achieve steam purity more quickly, providing additional lines for warm-up, and using an auxiliary steam boiler to reach desired condenser vacuum more rapidly are only a few examples of the measures that can be taken. However, many of these steps can significantly increase the overall cost of the project.

10.0 THERMAL PERFORMANCE

Contractually, the EPC contractor must conduct a performance test for the entire CC power plant to demonstrate to the Owner that thermal performance guarantees are met. However, on many occasions, component performance testing for GT, HRSG, and ST is also performed concurrently with the CC plant test. It should be noted that a new ASME Performance Test Code, PTC 6.2, is in the final stages of approval. This new code was conceived especially for STs in CC applications, wherein the power output is the only guarantee. The new code demands specific correction curves to account for the interaction between the HRSG and ST and sets forth stringent requirements for instrumentation accuracy.

The outcome of ST tests conducted by Bechtel for 13 units, manufactured by 5 different suppliers, is presented in Figure 2. As can be seen, many of the units did not meet their guarantees, and additional work was required to improve their performance. It is not hard to understand that some OEMs succumb to competitive pressures and offer aggressive performance guarantees.

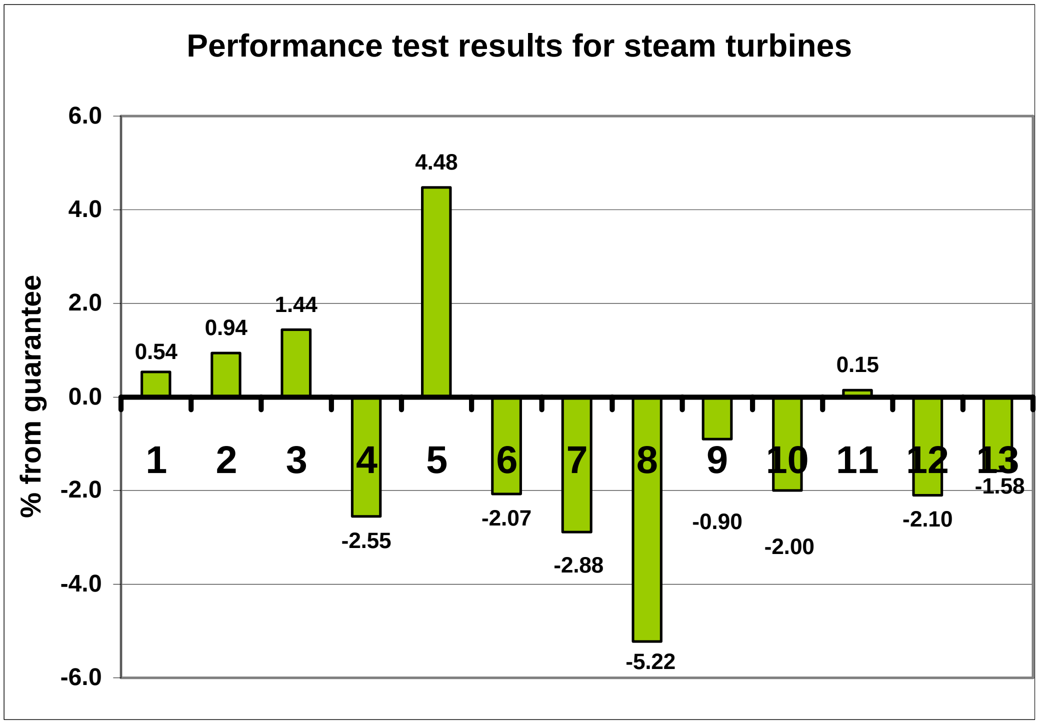

Figure 2. Steam Turbine Output Guarantee Test Results

11.0 SUMMARY AND CONCLUSIONS

Steam turbine manufacturers are investing heavily to improve turbine efficiency by reducing internal losses and by using improved construction materials. This process is ongoing, with high expectation of further progress. The equipment manufacturers have identified and corrected many deficiencies associated with introduction of new technologies. Regarding the failure of many STs to achieve their performance goals, Bechtel, as an experienced EPC contractor, has learned from this experience and has made provisions at the design stage as well as during execution to ensure that the total power plant performance guarantees are met. The integration of other major equipment (GT, HRSG, heat sink) was done to allow better-than-guaranteed performance. In a domain under its sole responsibility, Bechtel has implemented other design measures, resulting in additional design margins to compensate for the higher performance sensitivity of the ST’s high performance requirements.

Even though performance test codes governing plant testing are quite detailed, demonstrating performance shortcomings is not an easy task. Many issues are still subject to interpretation by the parties involved in the testing, in particular measurement uncertainty. Because of the significant monetary consequences, contract documents concerning test execution and the methodology to determine liquidated damages (or bonuses) must be very explicit, and the actual testing must be conducted "by the book," with the full participation of the equipment supplier.

Having executed a large number of projects with STs from all the leading manufacturers, Bechtel has accumulated a large database of actual performance. The lessons learned and best practices have evolved into a due diligence process that is used at the equipment selection stage of all new projects. The process is refined and improved as more data becomes available from newly completed projects.

Continuous effort and collaboration among Bechtel, owners, and equipment suppliers have been required to arrive at this juncture in process improvement. For all parties to accomplish their goals under these conditions, design and construction approaches had to align with the business objectives.

The relationships and modes of interaction among all the participants in building a power plant from conceptual design to final acceptance play a significant role in successful project outcome. Technical openness, free exchange of ideas, input based on personal experience, and most important, mutual trust among the parties provide the right ingredients for a successful project conclusion.

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