

STRATEGIES FOR INTEGRATION OF ADVANCED GAS AND STEAM TURBINES IN POWER GENERATION APPLICATIONS

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INTRODUCTION

Combined cycle power plants (CCPPs) using fossil fuel generate the cleanest and most efficient form of electrical power. CCPP technologies have evolved significantly in providing better, more cost-effective products: gas turbines (GTs), steam turbines (STs), heat recovery steam generators (HRSGs), heat sinks, pollutant removal technologies, balance of plant (BOP), water treatment and fuel treatment equipment, etc. A major reason for these improvements was the introduction of the G and H technologies for gas turbines, in which an inseparable thermodynamic and physical link was created between the primary and secondary power generation systems by using steam instead of air, in a closed loop to perform most (or all) turbine cooling activities.

A successful and reliable operation can be achieved only when all the components listed above are harmoniously integrated. This paper describes the challenges of the integration process from an engineering, procurement, and construction (EPC) contractor's perspective, based on the lessons learned from the execution of more than 30 CCPP projects in the last 5 years.

The integration process should start early on, at the project's inception, providing adequate solutions for all issues related to the development of the air permit and defining all processes based on site location, equipment arrangement, and operational flexibility. Various process configurations with targeted, sensible integration levels need to be reviewed. To match the best technology with a proven performance record and to recognize the long-term needs of the owner/operator, the contractor has to take a proactive role in selecting major equipment. The contractor role should not be perceived as only bridging the various power plant components, but rather, as designing and supplying complex control algorithms capable of ensuring startup, preheating, and load following, while remaining in full environmental emissions compliance.

Examples from several completed projects are provided in this paper to illustrate the challenges that an EPC contractor must successfully overcome to meet the technical requirements imposed by the new generation of GTs and STs. Finally, key recommendations from lessons learned are offered, which can be employed on future projects through judicious technology

assessment and equipment selection at the development phase and design optimization and proper project management at the execution phase.

AIR PERMIT

To get a head start on the increasingly daunting and lengthy permit process for a domestic power plant, prospective plant owners seek to obtain the services of an environmental consultant well before selecting the EPC contractor. In recent years, the permitting process in the US has become increasingly complex, requiring the involvement of several entities capable of identifying and quantifying the effect of the environmental commitments on overall project success.

A good approach is to involve the EPC contractor early. The contractor brings a larger view based on proven project designs, its database of lessons learned from other advanced equipment projects, and its startup/operating experience—a perspective that could closely reflect the owner's continuing objectives over the life of the plant.

Improving the Permitting Process

Since the air permit is usually secured as quickly as possible, "ideal case" assumptions are sometimes made. The concern is that key factors—project design, fuel selection, type of operation, back-end equipment selection, and performance—may be determined upon submission of the air application even if all pertinent information and inputs are not available. While this tactic is useful, it is invaluable for projects having advanced GTs as prime movers.

The process definitely requires a team effort. The environmental consultant provides valuable input to the permitting strategy, giving the owner and EPC contractor broader project perspective. Both owner and contractor will ultimately need to consider issues such as constructability, initial compliance testing, long-term emission compliance, and operability and maintenance. Consequently, the process should be structured and comprehensive, encompassing the following:

- **Detailed characterization of the fuels.** This characterization provides the basis for sizing the gas turbine and determining the amount of supplementary firing, which

ultimately define plant performance. This is followed by selecting the type and capacity of the pollution control equipment, performing steam cycle analysis, and determining heat and material balances necessary to generate pertinent emissions data for the air permit application.

- **Development of a site-specific arrangement and characterization of pollution sources.** If this arrangement is developed without a detailed design, the resulting layout is likely to represent a configuration that is unworkable from a design, construction, and operations point of view. Examples of key site arrangement issues include:
 - Power block arrangement and dimensions
 - Main stack height location and base elevation
 - Stack parameters of emissions sources (stack exit diameter, velocity, height, temperature)
 - Size and orientation of cooling tower
- **Definition and evaluation of supplier emissions guarantees.** The air permitting process also needs to be supported by credible emission guarantees from major equipment (e.g., GT, HRSG, auxiliary boiler) suppliers with experience and technical expertise in providing systems capable of demonstrating compliance within the proposed emission limitations. In many cases, the technical information from the suppliers is assessed using a model, which facilitates critical evaluation of the component performance by pollutant.
- **Definition of the startup/shutdown processes.** Increasingly, air permits include implicit or explicit emission limitations for the startup and shutdown periods. Although these emissions are often exempt from emission compliance determinations, many state permit writers include specific compliance conditions for the startup and shutdown periods. In some cases, these conditions address warm and hot startups and the number of annual starts. In other cases, the emission limits cover all periods of operation (i.e., with no exclusions for startup or shutdown) or define specific startup/shutdown emission limits (lb/hr, lb/MMBtu). In the current market, where merchant power plants need to account for daily starts and stops, such restrictions could directly influence the profitability of the operation. Therefore, it is essential to adequately characterize these special modes of operation and consequently determine the emission and load profiles. Limitations on startup emissions will also affect the specification of major plant equipment (i.e., GT, ST, HRSG, and auxiliary boiler).
- **Assessment of the impact of monitoring uncertainty.** In the past, measurement uncertainty was not an important issue, in part because compliance limits were large enough to make such margins less significant. The measurement methodology for emissions values was sufficiently accurate that both federal and state regulators considered stack and continuous emissions monitoring to be “presumptively accurate.” However, the influence of these protective factors has disappeared. Today’s ultra-low emission limits (below 2 ppm) especially for NO_x and CO, have almost eliminated any compliance margins. Since the uncertainty is a relatively larger percentage of the overall limit, actual equipment

emissions must be lower than the permit limits for the plant to remain in compliance (see Reference 1).

GAS TURBINES

Equipment Selection

Before selecting the equipment from different suppliers, a thorough investigation should be conducted to ensure that the owner’s pro forma objectives for power output, heat rate/efficiency, exhaust energy, emissions, reliability, and availability are met.

This process includes a technology review with the supplier to verify quality control for the engineering and manufacturing process (see References 2, 3, 4). In addition, the performance data offered by the vendors for a specific project must be normalized and correlated with the performance data from other projects using the same type of GT. The analysis should also include a comparison with other manufacturers’ competitive products. In the last 4 years, several models of GTs using steam cooling have accumulated substantial hours of operation and have accumulated meaningful availability and reliability data.

At Bechtel, the entire process is based on a performance database created by the company over time. The information in the database is constantly updated with results from field tests. Figure 1 represents a selection of 37 GT units recently tested by Bechtel.

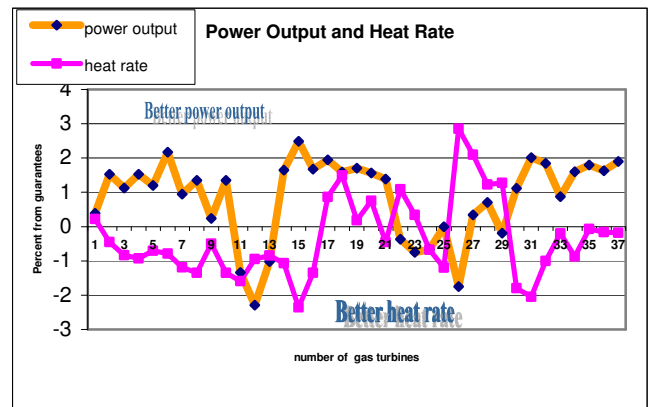


Figure 1. Comparison between guarantees and test results for GT power output and heat rate

In the current electricity market, some advanced GT original equipment manufacturers (OEMs) recommend a switch in the focus to reliability and operational flexibility rather than maximum efficiency (see Reference 5). CC using G or H class GTs with steam cooling will have a higher efficiency (varying between 1 and 2 percent); however, some operators believe they will require a longer time to start than the air-cooled F class GTs, particularly under cold conditions.

One other issue related to evaluating GT performance in CC plants is the requirement to evaluate (in addition to power and heat rate) exhaust flow and temperature. All four parameters are heavily interdependent. For example, if a GT operating at the design turbine inlet temperature exceeds the guaranteed power output, it usually has better-than-expected component efficiency, particularly for the turbine section. As a result, the exhaust

temperature is lower. A lower turbine exhaust temperature has a negative impact on HRSG steam production and, therefore, a lower ST output.

It is virtually impossible for any given GT to meet all four guarantees concurrently. When establishing the HRSG and ST design conditions, it is a good engineering practice to allow for some variability of GT exhaust flow and temperature values. This way, the design could accommodate either shortfalls or better-than-guaranteed exhaust energy (flow and temperature). Thus, more realistic and competitive values can be predicted for the CC performance.

Our experience indicates that owners/operators are well advised to engage an experienced and bankable EPC contractor in purchase or reservation agreements for GTs or power islands. As mentioned above, such collaboration becomes crucial for projects involving advanced GTs. The EPC contractor can verify that terms and conditions essential to managing project design, construction, and commissioning are adequately covered in these agreements. An EPC contractor, with direct experience with this type of GT, can also work with the equipment supplier and the customer to ensure that the scope is complete and all interfaces are well defined. Areas where the EPC contractor can add value to an owner’s reservation agreement include:

- Establishing adequate coverage of performance test tolerances and measurement uncertainty
- Addressing the impact of GT performance offsets (between power output and exhaust energy) on HRSG and ST sizing
- Ensuring pollutant levels and units included in the plant permits and GT supplier guarantees are consistent
- Evaluating technology risk issues (e.g., use of first-of-a-kind technologies and impact of the continuous design improvement process)
- Assessing the effects of cycling operation on the plant components and their interaction

Gas Turbine Experience List

In the last 5 years, Bechtel has been involved in the EPC phases of several projects using FX (generic designation of the latest models of F class technology [FA, FB, FD, etc.]) or G technology.

Table 1, which shows sites located around the globe and involving various types of GTs from four major suppliers, constitutes a good experience basis for the following detailed discussion of design and commissioning issues.

No. GTs	Type of GTs	Manufacturer	Country
18	7FA	GE	USA, Mexico
13	9FA	GE	UK, Turkey
4	GT26	Alstom	UK
6	V94.3A	Siemens	Netherlands, Egypt
4	W501G	Siemens	USA
9	W501FD	Siemens Westinghouse	Brazil, Mexico, USA
2	M701F	MHI	Egypt
56 Total			

Table 1 List of projects with Bechtel participation

Gas Turbine Startup and Commissioning Issues

EPC contractors are responsible for starting up a CC plant and incur significant penalties if successful, timely operation is not achieved. Therefore, EPC contractors must evaluate the cost-effectiveness of approaches that facilitate rapid startup. The problem becomes even more critical for merchant power plants, where cycling and part-load operation are often required. Depending on specific completion requirements and previous experience with a particular type of advanced GT, the startup schedule must allow time for unforeseen events. Some examples of these include:

- **Dual-fuel operation.** The design of an advanced GT focuses on using natural gas as the primary fuel. Dual-fuel capacity with oil as an alternative fuel is an option that attracts many owners because it can produce power when natural gas is not available. Dual-fuel capability adds even more complexity to already very complicated combustion systems and controls. A difficult challenge is to achieve a switchover from one fuel type to another at a reasonably high power level. For some manufacturers, this activity took longer than expected and affected the commissioning schedule.
- **Implementation of modifications in the field.** Several critical advanced GT integration lessons learned are related to field modifications. On many occasions, unscheduled outages are used not only to correct a problem but also to implement a number of changes based on experience accumulated from other sites. Significant modifications incorporated include not only physical changes in the hardware but also control software. This process creates a “ripple effect” requiring additional changes in the complete plant control software and start sequences. Managing these changes is critical to maintaining schedule on advanced GT projects.
- **Combustion system commissioning and tuning.** To meet the strict emissions requirements, all advanced GT combustion systems operate with dry low-NO_x (DLN) combustion systems. Combustion system operation from diffusion mode at low loads to full premix mode at base load takes place in several complicated steps and stages, requiring very close control of the fuel flow and exhaust temperature. The process is sensitive to ambient conditions, combustion-associated instabilities, and even manufacturing or assembly tolerances. Currently, each GT is individually adjusted to meet the performance guarantees and emissions requirements without combustion oscillations. This practice has become a standard feature of GT commissioning. However, this activity impacts the EPC contractor. The execution schedule is extended to perform a water wash of the compressor before the tuning process and to install and remove temporary instrumentation for full-blown performance testing of the GT. Because emissions limits must be met at all ambient conditions, adjustments made in the field might modify the performance correction curves for ambient temperature.

Additional Gas Turbine Lessons Learned

Advanced GTs with DLN combustion technology may require the ability to both heat and cool fuel gas during startup. As GTs proceed to higher outputs and efficiencies, the fuel gas supply pressure requirements typically exceed 30 barg and can sometimes exceed 35 barg for can-type combustion systems. These supply pressures often require supplemental fuel gas compression. During startup at low fuel flow rates, operation of supplemental compressors can result in significant increases in fuel gas temperature due to compression heat. However, DLN combustors typically require “cold” fuel for initial startup. As a result, a startup or pilot cooler may be required downstream of the supplemental fuel gas compressor. Later on, as the GT ramps up in load, heated fuel would be required for full pre-mix operation and the cooler would need to be isolated or bypassed. On projects with widely varying fuel gas supply pressures, supplemental compressors can often be bypassed, even during startup. Therefore, both a dewpoint heater and a startup/pilot cooler would be required for the fuel gas supply system to meet startup fuel gas requirements under all scenarios.

STEAM TURBINES

In the last 10 years, STs in CC applications have evolved significantly from small 80 MW, two-pressure, non-reheat configurations to large multiple admission pressure reheat turbines with outputs reaching the 350 MW range (see Reference 6).

Significant differences exist between STs designed for CCs and those designed for conventional Rankine Cycle (RC) applications. First, feedwater heaters are not normally used in the thermal design of the bottoming cycle for a CC. Second, because steam is admitted from several points in the HRSG, heat extraction from the GT exhaust energy is maximized. For the same high pressure (HP) main steam flow, the CC low pressure (LP) exhaust steam flow, when compared with the RC LP steam flow, can be up to 35 percent higher. Third, CC designs use duct firing to compensate for reduced GT output at high ambient temperatures, which coincides with maximum summer demand for power. In the US, it has also 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 suppliers to offer a compact plant layout with axial steam exhaust using only two standard cylinders, reducing the cost of manufacturing and installation as well as the erection schedule (see References 7, 8).

Although all ST manufacturers typically employ a modular building block system with standardized and corresponding components, during the plant design process, it is recommended to verify that the steam blade path should be modified. If an EPC contractor is the CC developer, it might use equipment from different manufacturers, thus requiring further optimization. Another example of optimization is operation with substantial supplementary firing.

Due to currently high natural gas prices, even small blade path changes can translate into operational savings. The customization of the LP steam turbine last stage path system is an additional case in which a “standard design” might not be the most suitable for the plant heat sink, especially for 2 x 1 and 3 x 1 multi-shaft CC configurations.

It should be noted that analysis of only the last blade will not suffice to define the LP turbine behavior. Given the intricacy of the aerodynamic and mechanical requirements, the design of the LP last stage must be integrated with that of the two previous stages in a complete LP steam path system.

Traditionally, development efforts to increase overall ST efficiency have focused on improving the HP and intermediate-pressure (IP) modules. However, in the last few years, equipment manufacturers initiated ambitious plans to upgrade the LP turbine, which, in many cases, represents a substantial percent of the total power generated. A larger last-stage blade size means a higher power output at lower condenser pressures.

Furthermore, performance optimization should be conducted not only at the design point but also for the entire operational envelope.

Figure 2 shows the typical thermal efficiency values for three modules (HP, IP, and LP) recorded on 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 in 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.

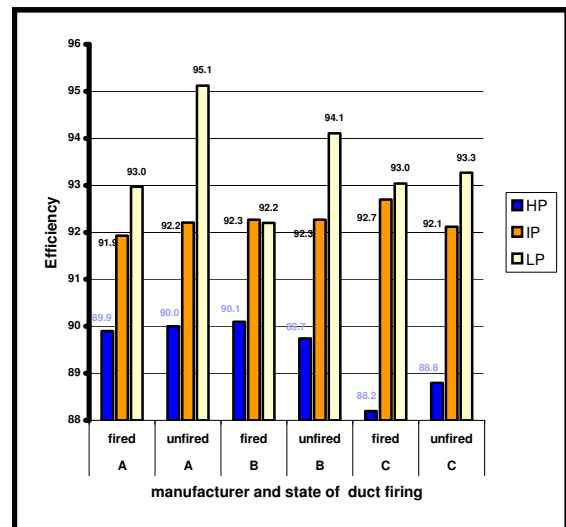


Figure 2. ST module efficiencies for duct-fired and unfired cases

Steam Turbine Equipment Selection

Before selecting equipment from different suppliers, a thorough investigation is necessary to verify 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 (see References 9, 10). Similar to the GTs, the ST performance offered by OEMs is normalized and reconciled with past performance of the same equipment in a similar configuration 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 in which decisions regarding selecting cycle pressures and locating the steam extractions are limited by the commercial availability of STs that can meet the specified conditions. Another decision needed on most cogeneration projects is whether to design the ST and associated steam cycle equipment for a case in which no steam is required for the process. In this scenario, a larger LP section and an increased downstream electrical equipment (transformer, isophase bus, etc.) capacity are required. In this decision process, economic benefits of the extra power availability and operational constraints due to possible infrequent occurrences of such conditions should be carefully considered (Reference 11). The selection process should be transparent and capable of evaluating not only the technology risks associated with the equipment itself but also the integration risks.

Increasing the last-stage exit area is a key factor in reducing plant capital cost and minimizing exhaust losses. For cycling plants, however, more work is necessary to demonstrate that the efficiency as well as aero-mechanical behavior during part-load operation are not much worse than in the conventional design.

Exhaust Loss Curves

One of the important features of STs used to integrate other components and, in particular, optimize the heat sink is the exhaust loss curve. The ST thermal kit provided by the manufacturers to plant designers contains information on LP exhaust losses in the traditional form of an “exhaust losses curve.” This curve gives the specific enthalpy loss for an exhaust average steam velocity. The steam velocity value depends on the back pressure and/or steam flow. The use of this curve requires corrections for moisture content (see Reference 9). Since the average steam exhaust velocity is a function of the volumetric flow for a given geometry, its value depends on both back pressure and steam mass flow. Figure 3 provides a number of exhaust loss curves for various exhaust areas. The increased exhaust loss at lower exhaust velocities (less than 550 feet per second [fps]), occurring at low part-load conditions, is due to the formation of a reverse vortex at the blade root.

Development of new generation and often non-conventional profiles, with large variations along the blade height, has produced considerable benefits in terms of the stage’s efficiency and reduced exhaust losses. Figure 4 presents the exhaust curve loss for blades from two manufacturers that have almost identical exhaust and blade lengths. It can be concluded that a more advanced 3D profile design (Curve A) leads to a lower exhaust loss. Since the total exhaust loss curve also includes the

contribution of the exhaust hood, its design should be aerodynamically effective.

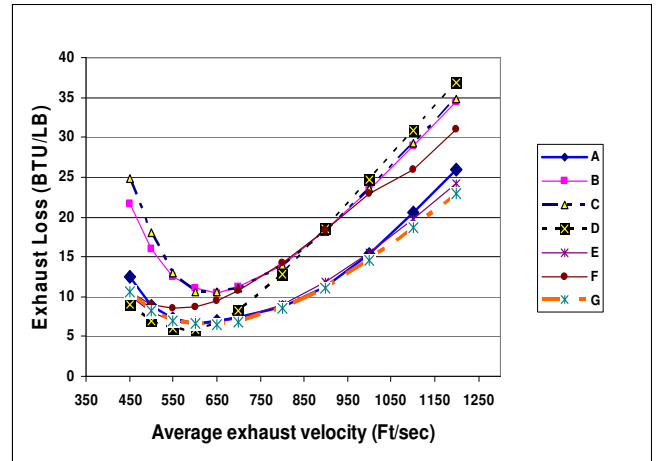


Figure 3. Typical exhaust loss curves from different manufacturers.

Given the complex aerodynamic and mechanical effects of modern 3D blade profiles, with very different characteristics between the hub and the tip, the tone-dimensional, conventional description of an exhaust average needs to be replaced by a more accurate representation, either a multi-variable curve function of blade geometry and exhaust conditions or a software simulation package.

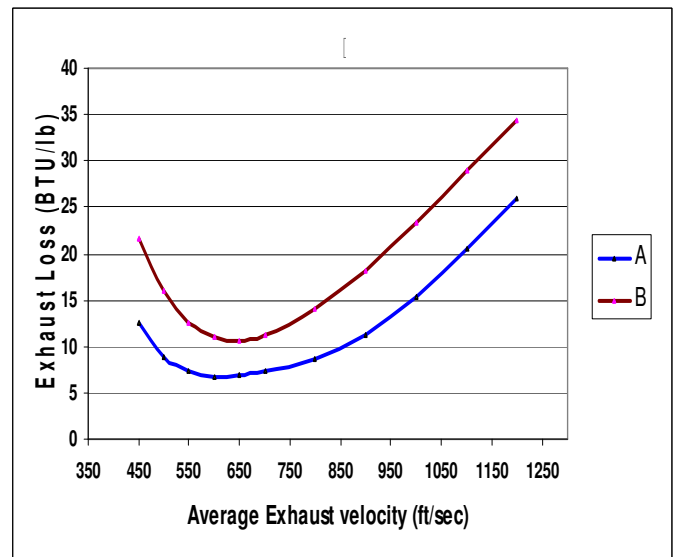


Figure 4. Exhaust loss curves from two manufacturers (very similar exhaust area and blade length)

Steam Turbine Experience List

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 30 projects, installing and starting up 56 GTs and 40 STs.

Table 2 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.

Supplier	No. of Units	Nominal Power (MW)	Characteristics	CC Configuration
Alstom	7	250		2 x 1
Alstom	12	85/155	Unfire /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	Desalination noncondensing unit	1 x 1
GE	3	200		2 x 1
Hitachi	2	250		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	40			

Table 2. STs from major suppliers.

Steam Turbine Startup and Commissioning Issues

ST startup flexibility and commissioning time play a significant role in startup of the entire CC plant. Due to higher fuel costs and increased electrical reserve margins, CC plants are dispatched as intermediate-duty units rather than base load units, as originally envisioned. Achieving the goal of a fast and reliable startup requires careful design and integration of the ST, GT, 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, 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 the process. Examples of such measures include means to improve the heat retention after shutdown, design of advanced water treatment systems capable of achieving steam purity more quickly, provisions for additional warmup lines, and use of an auxiliary steam boiler to reach desired condenser vacuum more rapidly.

Additional Steam Turbine Lessons Learned

Some GT/HRSG/ST combinations are better suited for rapid cycling than others. It is not possible to accurately predict CC power plant startup times from the typical startup curves for each piece of equipment. Each major equipment vendor will make assumptions about startup conditions that are most favorable for that vendor's individual piece of equipment. These assumptions are usually different, often conflicting, and sometimes incompatible. The overall startup integration must be considered early in the project, and consistent requirements need to be provided at the bid phase for each vendor. The drive to increase ST efficiencies results in tighter clearances to reduce leakages, but these usually require longer startup times to avoid rubbing and reduce thermal stresses. Stringent steam temperature matching requirements may also be requested. These requirements vary between ST vendors and cannot always be met by every GT/HRSG combination. The GT operating at low loads has a limited capability to maintain high exhaust gas temperature. This capability varies significantly between manufacturers. Combining a GT with limited ability to control exhaust gas temperatures at low loads with an ST that has very strict temperature requirements at startup can lead to unacceptably long startup times (greater than 8 hours) for cycling units. The HRSG may not be capable of accommodating the GT and ST requirements simultaneously without significant bypass capability. Although this scenario might seem unlikely to occur, Bechtel has witnessed this circumstance more than once, when owners procured each piece of major equipment separately, considering only performance and price with no attention to integrated startup requirements.

Cycling Considerations

The merchant plant concept implies that electric power must be supplied to the grid only when it is commercially justifiable. Such operation requirements must typically be met on very short notice. Therefore, these plants need to be started up quickly and must have flexible operating ranges. Merchant plants are normally in cycling service, which can be considered part-load operation or daily on/off duty. Heat sink considerations for a cycling plant include the following:

- Use an auxiliary boiler to sparge the condenser hotwell to prevent the condensate from subcooling
- Maintain condenser vacuum during periods of shutdown
- Use a cooling tower bypass for low-load operation
- Use pre-coat condensate treatment (condensate polisher) with air-cooled condensers, which may have large carbon steel surface areas in contact with steam and condensate
- Include provisions to control all heat sink fans from the control room

For cogeneration plants, the quality and quantity of water returned to the power plant from the process must be considered. Depending on the quality of the returned water, further deaeration and chemical treatment may be necessary. If not all the exported water is returned, additional cycle makeup will be required. An external deaerator will be required if the total cycle makeup exceeds 3 to 5 percent.

BALANCE OF PLANT

Balance of Plant Equipment Selection

BOP equipment for a CCPP includes boiler feedwater pumps, condensate pumps, circulating water pumps, closed cooling water pumps, air compressors, fuel metering equipment, etc.

Proper system integration of BOP equipment also requires that interconnecting piping/support systems be optimized to the power island (GT, ST, HRSG, heat sink). Based on the arrangement of the plant and amount of BOP equipment, the engineering evaluation will start by determining the amount of circulating water, steam, air, and fuel required to operate the plant at the expected power output.

The optimization of sizes, material, layout, and cost of BOP equipment and critical piping is no less important to the performance and cost of the entire plant than the power island major equipment. One of the important lessons learned was to review and continuously validate the specifications for each of the major BOP systems (main steam, feedwater, condensate, and circulating water) to rapidly respond to new requirements and incorporate the experience gained from previous projects.

Auxiliary Loads

A critical step in each project is to assess, with a high level of accuracy, the plant's total auxiliary load at given guaranteed conditions. Auxiliary loads, representing the amount of power consumed by each piece of equipment during normal plant operation, can vary significantly due to the type of equipment and its configuration. The theoretical estimation at the beginning of the plant design must also be confirmed during performance testing. This process requires a careful engineering evaluation of the equipment in operation and the utilization factor to be applied to each piece of equipment.

A good indication of a successful design is to achieve a close match between the auxiliary load calculated and the actual values measured during the test. By conducting upfront detailed engineering to obtain actual pump performance curves and using a database of past projects' auxiliary loads (both calculated and measured), Bechtel was able to predict with a very high degree of accuracy the auxiliary loads for the projects associated with the turbines presented in Tables 1 and 2.

Material Selection

Tailoring material selection to the specific operating conditions of the power plant reduces the cost and ensures proper plant operation. Over the years, Bechtel has developed a material selector guide that assists the design engineer in selecting the proper material and in matching its properties to the required design parameters.

One interesting lesson learned relates to the selection of a high temperature pipe material. In the initial stage, the selected material was adequate and met the operational requirements. However, a better material, which exceeded the requirements, was found to be less expensive because the pipe diameter could be smaller and a standard schedule size could be used instead of minimum wall pipe.

In another example of tailored material selection, metal pipe was replaced with high-density plastic in a low pressure and temperature application, resulting in substantial savings.

Water Chemistry

Controlling the amount of dissolved oxygen in the condensate is critical, especially during startup. The most critical operational backstop to prevent dissolved oxygen (DO) from entering the feedwater is to avoid breaking condenser vacuum overnight (or ever). Maintaining condenser vacuum and preventing the hotwell from subcooling dramatically decreases the morning startup time and almost eliminates the huge swings in chemistry associated with cold startup. Following are lessons learned on how to minimize corrosion potential due to DO:

- **Use an auxiliary boiler.** For units that shut down completely at night, an auxiliary source of steam is used to maintain steam to the ST seals, thereby sustaining condenser vacuum. This auxiliary steam source is also used to sparge the condenser hotwell to prevent the condensate from subcooling and picking up DO. Additionally, the condenser sparging system is used during part-load conditions to prevent subcooling of the hotwell. The auxiliary steam source also minimizes the amount of makeup demineralized water required to support operation of the sky valves.
- **Design the condenser vacuum system to utilize LP motive steam to power the steam jet air ejectors (SJAEs).** If using vacuum pumps, verify that the vacuum pump cooling water supply is cold enough to stay ahead of flashing due to low vacuum conditions. A hybrid system can also be used (an arrangement where vacuum pumps take suction from SJAEs).
- **Consider putting the ST gland steam condenser on the closed cooling water loop.** Doing this will eliminate the need to operate the large condensate pumps during shutdown.
- **Always maintain a positive pressure in the HRSG drums during shutdown.** This is accomplished by closing the stack damper and all outlet valves to the HRSG after the GT is secured. At least approximately 8 to 16 hours are needed to cool the HP drum to saturated conditions of 400 to 500 °F. After the boiler has cooled to within the range of the auxiliary steam source pressure, open the HP evaporator spargers and keep the drum as close as possible to drum soak conditions. This would constitute a warm start of the HRSG with no ramp-up restrictions. The heat migration from the HP section to the IP and LP sections of the boiler will tend to keep those drums at significant pressure. The LP drum must be vented throughout the night to prevent overpressurization.

If the HRSG is taken off line for maintenance under cold conditions, apply and monitor a nitrogen blanket above all water spaces and follow the manufacturer's recommendations for chemical dosing of the drums. As the steam space pressure decreases, align the nitrogen system to push and replace the steam, which will minimize air in-leakage.

SUMMARY

The number of CCPPs based on advanced GTs has steadily increased over the last 7 years. The equipment manufacturers have identified and corrected many issues associated with

introduction of new technologies. The units have started to log a sufficient number of hours to obtain quality availability, operational flexibility, and reliability data.

Having executed a large number of CC projects, Bechtel, as an EPC contractor, has not only implemented lessons learned from previous projects but also refined and improved the design and execution methodology of new CC projects.

The road to this juncture was neither simple nor easy. A continuous effort and collaboration between equipment suppliers, contractors, and owners are necessary. For all participants to achieve their goals under these conditions, design and construction approaches must align with business objectives more than ever. The relationships and modes of interaction among all the participants, from conceptual design to final acceptance, play significant roles in the successful outcome of a project. Technical openness, free exchange of ideas, personal experience input, and most importantly, mutual trust among the parties form the right ingredients for a successful project conclusion.

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