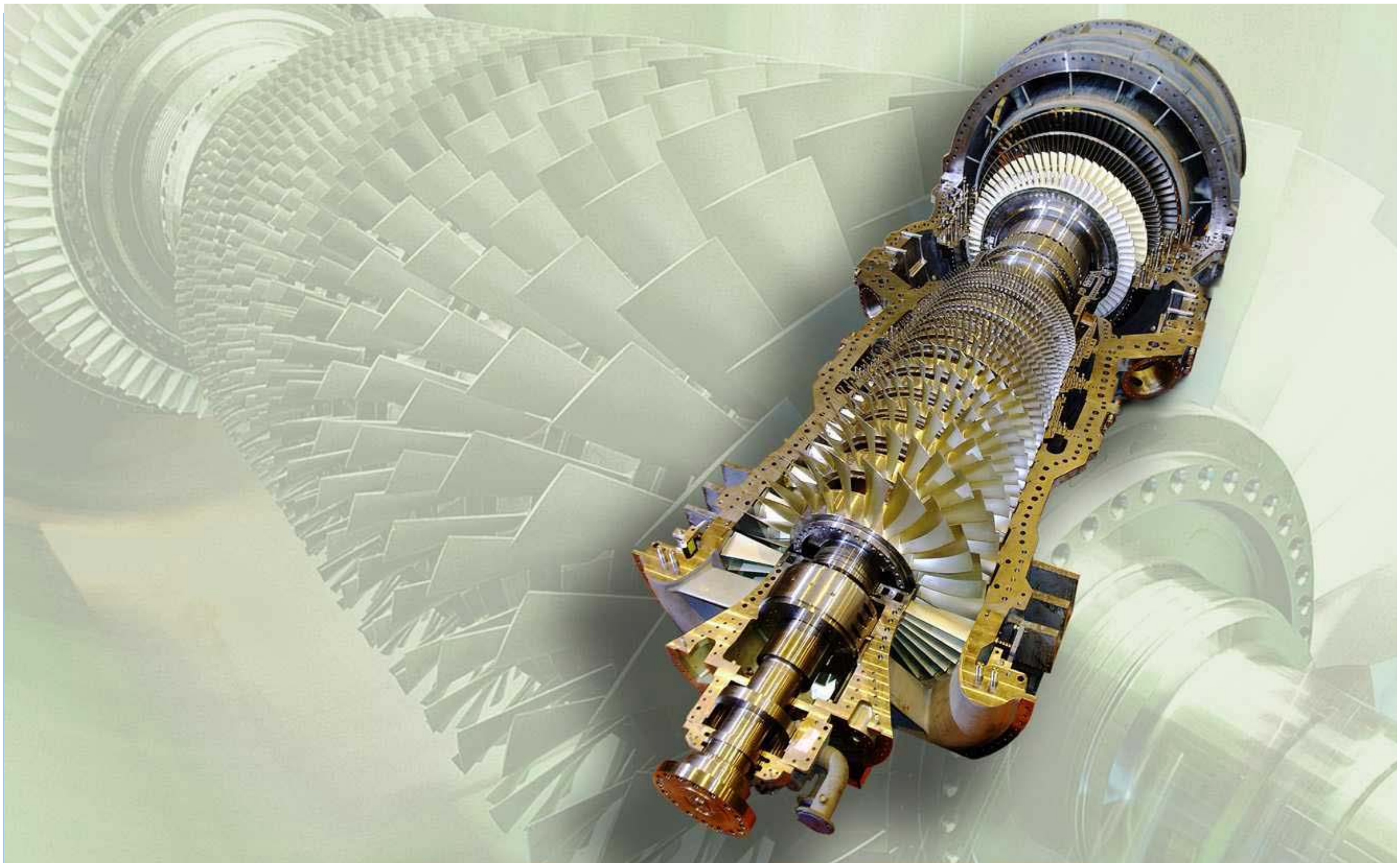

An Integrated Combined-Cycle Plant Design That Provides Fast Start Capability at Base-Load

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An Integrated Combined-Cycle Plant Design That Provides Fast Start Capability at Base-Load Efficiency

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ABSTRACT

While efficiency is still the major driver in combined-cycle power plant design, there is an increasing need for operational flexibility along with additional operating cost reduction. Nightly and weekend shutdowns and subsequent start-up capabilities should be considered during the overall evaluation of a power plant. Technological advancements in power plant design involving gas and steam turbines, heat recovery steam generators (HRSGs), generators and comprehensive plant component integration have increased thermal performance and allowed greater operational flexibility.

Advancements in gas turbine technology have increased power and efficiency while decreasing emissions and life-cycle costs without sacrificing reliability. Siemens advanced gas turbines are equipped with 3-D aero blading, high temperature tolerant coatings, advanced cooling technology and low emissions combustion systems. These features have been incorporated into a well-proven technology base that includes many gas turbine design features that have been adopted as industry standards.

Despite advances in gas turbine power and efficiency, when used in combined cycle-application, plant owners were traditionally forced to choose between high efficiency or operational flexibility (at the expense of efficiency). Although it has always been important to provide operational flexibility in order to enhance the value and agility of power generation assets, it has not been economical. Gas turbines have traditionally been required to compromise their fast-loading capability to accommodate the limitations of the HRSG, steam turbine and other components. By properly designing and integrating the plant components to allow a fast start capability while dramatically reducing start-up fuel and emissions as well as water consumption, an economical solution is now available. Plants capable of achieving traditional base-load combined-cycle efficiency, incorporating fast starting and cycling capability now allow owners to meet a variety of challenging and sometimes changing market demands.

This paper addresses results of a comprehensive integrated program within the authors' company to develop the Fast-Start Plant; A combined-cycle plant design that offers fast starting and cycling flexibility without jeopardizing efficiency or reliability. This plant design integrates proven plant concepts with highly efficient components and advanced technology to exceed the capabilities of existing combined-cycle plant designs.

INTRODUCTION

From a plant capability standpoint the changing operational regime toward more intermediate duty significantly compromises its economics, especially when the asset is designed for base-load operation. The effect of "hidden" or unknown costs caused by this change/shift has been discussed in detail [1], stating that the real cost of cycling appears in the form of increased forced outages, lost production, increased frequency of failures in HRSG and steam turbine components, etc.

The major challenges facing asset managers with plants operating somewhere between intermediate and continuous-duty are responding quickly to dispatch demands during high-profit opportunities and dispatching while revenue generation is feasible. The majority of combined-cycle plants recently built do not fully support these challenges and little progress has been made to overcome this situation. Several publications have already outlined existing industry practices on plant cycling [2]. The recommendations in these include obvious scope provisions for auxiliary boilers, automated drains and vents, etc. This paper will not elaborate on these.

Instead, it will address the challenges to EPC contractors to develop improved plant concepts incorporating the latest advancements in GT technology and cycle integration that go beyond current considerations for plants designed to cycle.

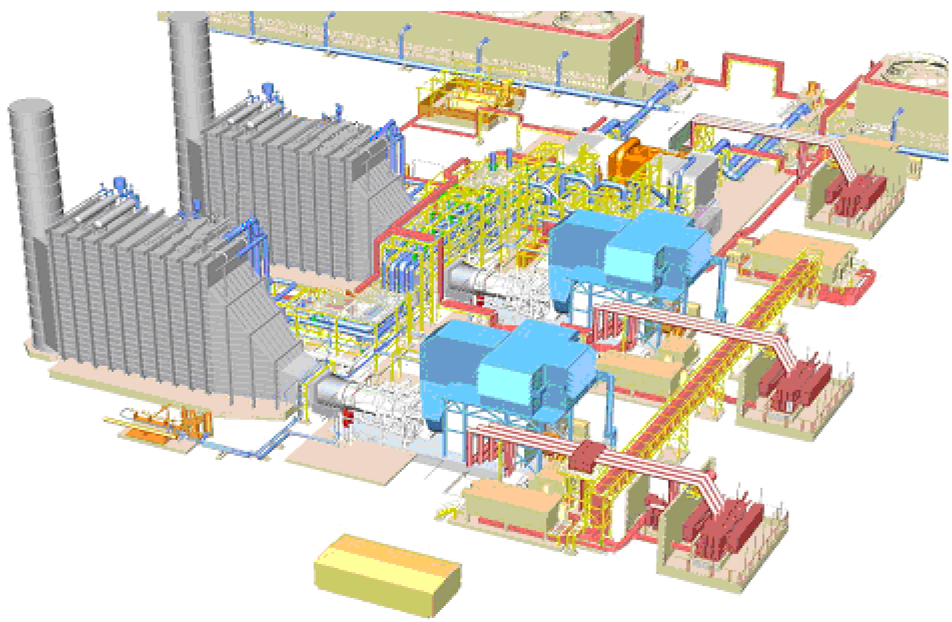

Figure 1 *The 2.W501F Fast-Start Plant*

This paper introduces details on the authors' company's integration of advanced GT technologies into fast-start combined-cycle plants that address the following challenges faced by operators:

- Increased operating costs due to fuel gas consumption during non-dispatched times (ie. Startup)

- Gas turbines being operated for a prolonged period of time and more frequently in higher emission operating regimes, which may encumber emissions permitting and operational flexibility
- Lowered revenue and/or permitting issues due to increased demineralized water consumption

ADVANCED GAS TURBINES

Siemens Power Generation (PG) has implemented advancements in industrial gas turbine technologies in both 50 and 60 Hz gas turbines. Aerodynamic enhancements combined with high temperature tolerant materials, sealing improvements, component cooling and combustion system design improvements have been integrated into the operating fleet. Advanced technology engines incorporate these features with combined-cycle technologies to achieve increases in plant power and efficiency.

Over five decades of gas turbine experience is manifested in Siemens PG's global fleet of reliable, highly efficient and economical 50 and 60 Hz gas turbines with ratings up to 270 MW. We leverage our extensive OEM experience and technical leadership to continually incorporate improvements in industrial gas turbine technologies into combined-cycle plants. When applied in combined-cycle configurations, these high power density engines produce net plant efficiencies ranging from 56% to greater than 58%.

The Siemens F- and G-class engines share several common design attributes that are found on engines dating back to the 1960's. The evolutionary design approach and product maturation philosophy employed by Siemens PG is apparent in examining these engines. Some common features of the base design include single variable inlet guide vanes (IGVs), interlocked discs, 3-D blading, a 4-stage turbine, two bearings, axial exhaust and cold end-driven generators. Many of these features have set industry standards for gas turbine design (See References 3 through 6).

EXPERIENCED AND PROVEN GT TECHNOLOGY

Siemens' advanced gas turbines satisfy the requirements of today's power investor by providing low capital costs, small footprint size, short construction periods and low operating costs. They continually meet the expectations placed upon them and provide the reliability and availability needed to compete in today's power markets. It is anticipated that by December 2003, there will be over 300 advanced technology Siemens F- and G-class engines in operation.

These engines have operated in a variety of modes. From peaking applications to continuous duty units, they have accrued operating hours through the entire ambient temperature range validating their designs. The F-class engines have accumulated over 2.5 million hours of operation and the four lead units have operated in a continuous base-load profile for over ten years averaging over 80,000 hours each. The W501G engines, working at full G-class temperatures, are on track to accumulate over 80,000 hours of operation by the end of 2003 with the lead unit surpassing 14,000 hours.

Many combined-cycle plants have operating regimes ranging from intermediate to continuous duty. Siemens has developed highly integrated combined-cycle solutions that achieve high efficiency while meeting this range of operation.

PLANT DESIGN CONSIDERATIONS FOR FAST-START / CYCLING CAPABILITY

In today's market conditions it is assumed that combined-cycle power plants require the operational flexibility that allows them to operate anywhere between intermediate and continuous duty with the same efficiency as that of an advanced technology base-load continuous duty plant. It was found that the long established differentiation between hot, warm and cold starts with the corresponding downtime assumptions of 8 hr (hot), 48 hr (warm) do not really reflect current operating scenarios. Therefore the Fast-Start Plants are oriented along the following more challenging operating regime:

	Down time	Starts per year
Overnight	8-16 hr	200
Weekend	up to 64 hr	50
Extended	>64 hr	2

In order to increase the plant operational flexibility eight additional extended shutdowns were taken into consideration for component lifetime evaluation. While the plant is designed to accommodate the 260 starts per year with approx. 4000 hrs. per year, it preserves its base-load operating capability. The flexibility of the design allows any combination of the number of Overnight, Weekend and Extended Starts – up to 260 starts per year.

With regard to start-up, the plant components restrict each other in terms of maximum allowable gradients/transient or necessary soaking time. This is an effect of interdependent systems and cannot be neglected. However, under the umbrella of the Siemens Reference Power Plant (RPP) program, experts (including vendors) from various disciplines (gas turbine, steam turbine, plant engineering and HRSG engineering), were brought together to integrate component and system designs to enable the following:

- The gas turbines (GT) load to be ramped up in combined-cycle applications as quickly as they are in simple-cycle applications, unrestricted by downstream components including the HRSG and ST
- The ability to vary and quantify the impact of a start-up on the steam turbine maintenance schedule, enabling the asset manager flexibility in setting a business strategy considering the ST and HRSG along with GT maintenance

The result of the development was successful as shown in Figure 2 for a start-up of a 2x1 F-Class plant after an "extended" overnight shutdown. The chart compares the relative power output dispatched by the "Fast-Start Plant" and a "Typical Plant". Both configurations consider three-pressure reheat bottoming cycles.

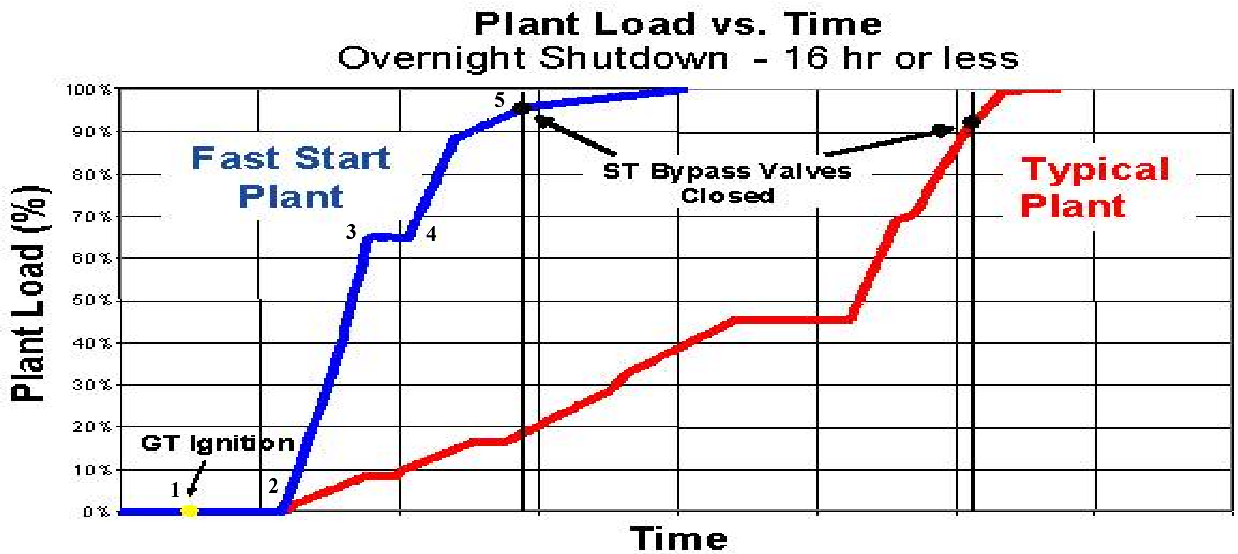

Figure 2 *Plant power output during start-up after overnight down time of 16 hours*

The Fast-Start Plant start begins with concurrent ignition of both gas turbines (1); the gas turbine generators are synchronized at (2). After an unrestricted GT ramp-up the GT's reach rated power at (3). At this point the steam turbine is also rolled off. The ST generator synchronizes at (4) while the hot reheat and low-pressure system bypass valves are closed at (5) and the ST accepts all generated steam. At this point the plant reaches approximately 97% of its rated power output.

This optimized start-up scheme makes the Fast-Start Plant's start-up approximately one-half that of its predecessor after overnight and weekend shutdowns. One of the key enablers for this improvement is Siemens' patented Benson®[1] Once-Through Steam Generator (Benson-OTSG), which can readily be applied with and without duct firing and SCR/CO-catalyst systems.

Benson Once -Through Steam Generator (OTSG)

The Benson technology has proven its capability and reliability over the past 70 years. This technology is well known throughout the industry in both sub- and supercritical designs in conventional steam power plants. Approximately 1,000 Benson boilers with a cumulative steam output of more than 700,000 tons per hour have been built to date.

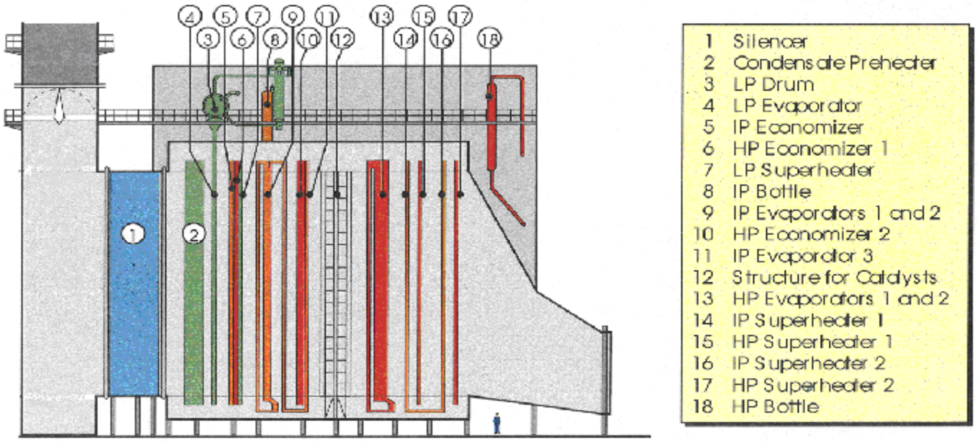

Figure 3 *Benson-OTSG at Cottam Development Center (three-pressure reheat steam cycle)*

[1] Benson is a registered Trademark of Siemens Aktiengesellschaft

The authors' company also successfully applied the Benson evaporator principle in a 390 MW combined-cycle application [7] at Cottam Development Center, Nottinghamshire (United Kingdom). This state-of-the-art single-shaft facility owned by Powergen plc has been in commercial operation since 1999. During this period the Benson-OTSG (Figure 3) has shown its direct applicability for fast-start up and cycling operation, even though the Cottam plant was not explicitly designed for this duty.

Based on the increased market demand for fast start-up/shutdown and cycling capabilities and the successful testing and operating experience at Cottam, the Fast-Start Plants incorporate the Benson-OTSG in their designs. Due to industry problems encountered with once-through technology of other HRSG suppliers, the design features that distinguish the Siemens Benson-OTSG from other once-through designs will be detailed/described.

The evaporator stage is characterized by two bundles of vertical tubes, which are arranged in series in the horizontal gas-path (Figure 4). All tubes within an evaporator bundle are connected in parallel, creating natural circulation characteristics. The low mass flux design allows the fluid mass flow to self-adjust to the heat input in each tube row, meaning tubes with higher heat absorption will see an increased fluid mass flow. This design ensures static and dynamic flow stability throughout a wide load range. In addition it results in lower pressure losses across the evaporator compared to other once-through concepts.

The Benson-OTSG is capable of handling high temperature transients during a fast start-up due to the elimination of thick-walled steam drums. The HP drum, in particular, impedes fast start-up of conventional HRSGs by dictating long soaking periods and slow maximum allowable temperature ramp rates. The Benson-OTSG eliminates these restrictions by replacing the drum with a small separator vessel, which also provides a more economical arrangement. The separator performs the function of water/steam separation during start-up and shutdown. At steady-state operation, including low loads, the steam flow passes through the separator, as part of the interconnecting piping toward the superheater. The steam at the evaporator outlet is slightly superheated; consequently no separation occurs.

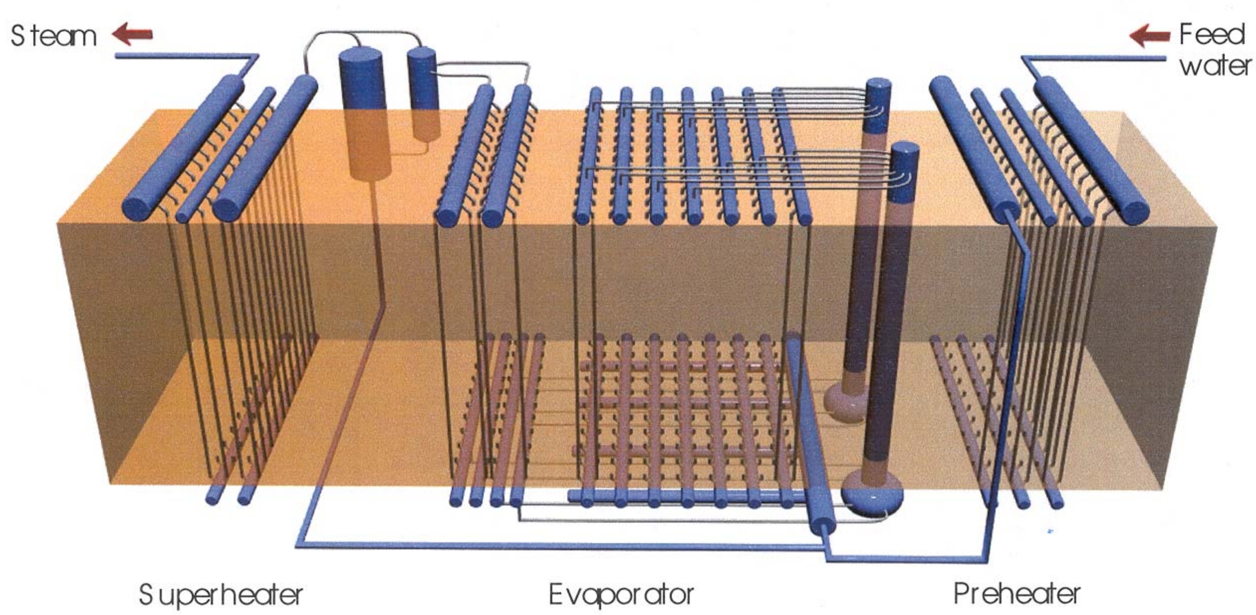

Figure 4 *Benson Once-Through Steam Generator Section*

Another common feature of once-through technology is utilized to control the main steam temperature. In contrast to a drum-type HRSG, the Benson OTSG is able to control the main steam temperature by modulating the feedwater massflow. This enables the system to compensate the effects of changing ambient conditions or GT loads within a certain range without placing the steam attemperators in operation. Attemperators are incorporated as interstage, as well as final-stage desuperheaters for the high pressure and reheat steam systems. This arrangement ensures compliance with the steam temperature limits, dictated by the steam turbine, during plant start-up.

Simply stated, the Benson-OTSG retains all the positive features offered by the traditional drum-type HRSG, including provisions for SCR, CO catalyst, duct firing, steam power augmentation, etc., while providing additional operating flexibility over drum-type HRSGs.

Steam Turbine

The steam turbine (ST) is started with power-output in mind, which means that it is rapidly loaded with reduced and nearly constant steam temperatures until the bypass valves are closed with the GT's at base load. This start method eliminates steam vents to atmosphere at the HRSG, due to the incorporation of an auxiliary boiler. Since there are no HRSG- or ST-induced holds of the GT start-up process, special care must be taken in the handling the generated steam in order to meet the optimal steam temperature for fast loading of the ST.

The steam turbine is designed for full-arc admission without the use of a control stage. This design greatly reduces blade stresses during the start-up process. The combination of full-arc admission with variable-pressure operation (which has become a standard for HRSGs in the industry) provides high efficiency, maximum operating flexibility and minimized maintenance.

The application of high-capacity steam bypass systems for HP, IP and LP steam is key to the operating flexibility and reliability/availability of any plant. The fast-start plants incorporate special provisions to route the HP bypassed steam into the cold-reheat of the HRSG to minimize thermal stressing of the HRSG reheater section during start-up.

In order to provide further flexibility, the authors' company's patented Turbine Stress Controller (TSC) is supplied [8]. The TSC consists of a stress evaluation system based on a ST start-up program with an on-line life cycle counter. It calculates and controls stresses in all critical ST "thick wall" components (including the valves, HP casing and rotor body and the IP rotor body) depending on three different ramp rates, i.e. planned, accelerated and fast. The function of the TSC is to control the start-up ramp rates in order to minimize material fatigue within the constraints of operating requirements and at the same time to calculate the cumulative fatigue of the monitored turbine parts. The TSC assigns an appropriate number of equivalent starts for each planned, accelerated and fast start. With this knowledge of the effect of each type of start on the maintenance schedule of the steam turbine, the owner can make prudent business decisions regarding whether or not the asset should be used to satisfy transient dispatch requirements.

Steam/Water Cycle and Operational Chemistry

While the power market requirements have changed and many combined-cycle plants are being operated closer to intermediate duty with demand for fast start-up/shutdown and cycling capability, asset owners still expect base-load plant efficiency levels. This is achieved not only by retaining the triple-pressure reheat steam/water cycle, but also by integration of the GT and cycle to maximize efficiency through systems such as rotor air cooling, fuel gas heating and steam cooling of the GT transitions (in the W501G).

This cycle design has been thoroughly analyzed and as previously mentioned was first introduced at the Cottam Development Center. The Benson-OTSG is a once-through steam generator for the HP and IP sections (IP as required), while the LP section (and IP as required) retains a drum-type design. This HRSG configuration requires a combination of pH-control with ammonia and oxygenated treatment. The oxygenated treatment creates and maintains a protective layer of magnetite and hematite inside the tubes.

As a further enhancement to rapidly achieve proper steam quality and to support rapid start-up, the cycle incorporates a condensate polisher. The polisher provides high quality feedwater to the Benson-OTSG thus avoiding deposits in the evaporator tubes and thereby decreasing the evaporator pressure losses. The condensate is deaerated in the condenser hotwell by vacuum, while the polisher removes the ammonia, which must then be added to the polisher effluent for proper pH-adjustment.

The combined oxygen/ammonia treatment with the integrated condensate polisher of the fast-start plant has already contributed to the high reliability of Cottam Development Center (Figure 5) and reduced the time to meet steam purity requirements to minutes [9].

Figure 5: *Cottam Development Center*

BOP Considerations for Fast Start-up/Shutdown and Cycling Operation

Let's reflect now on the impact of additional measures that support combined-cycle power plants in coping with the requirements of fast start-up/shutdown and cycling operation mode. As most of the readers that are associated with the power industry may already know, these measures can be acknowledged as industry standards and are also part of drum-type HRSG cycles. Noteworthy measures that are also applied in the fast-start plant are:

- Component redundancies
- Auxiliary boiler
- Vacuum pumps
- Stack damper
- Automated drain and vent valves
- Optimized steam piping warm-up concept
- High level of system and plant automation

BENEFITS

The fast-start plant as described in this paper offers numerous operating benefits that will positively affect the life-cycle costs (and thereby also the proformas) of a combined-cycle power plant. Since this plant can be operated equally as well (without an efficiency impact) in fast-start, intermediate-load or base-load modes, there is no need to optimize or design for one operating regime over another. The benefit of such dispatch flexibility can be invaluable. Furthermore, the ability to reach dispatchable load rapidly allows the owner to participate in more revenue generation opportunities. There are other advantages that can be quantified, including:

- Reduction of Emissions
- Fuel savings
- Decrease in Water Consumption

Regarding emissions, the only thing certain is that reducing total plant emissions is going to be a benefit for the facility. This means that the importance of start-up emissions will be amplified as the facility tries to maximize flexibility. Without the cycle restricting the GT ramp rate, the GT reaches a low emission level rapidly producing less total emissions per start-up. The plant thus has a significant reduction in start-up emissions due to the GT reduction coupled with the benefit of any post combustion emissions controls (i.e. SCR or CO catalyst). The additional benefit, which is difficult to quantify generically, is that without these emission reductions, plant operation could be restricted or curtailed, e.g. in non-attainment areas.

Due to the lifting of cycle restrictions on the GT start-up, the fast-start plants significantly reduce the fuel required for start-up. This results in a savings of approximately $2.8 million a year ($23.7 M over 20 years) when the 2x1 W501F is operated in a nightly and weekend shutdown scenario.

Since the fast-start plant eliminates start-up vents, there is also a saving in water consumption of almost 6 million gallons per year (approximately 63,000 m^3) for the 2x1 W501F.

It is obvious that the fast-start plant has a very positive impact not only on the plant's economics and operational flexibility, but also on the environmental impact due to its enhanced part load capability, without sacrificing high efficiency for base-load operation.

CONCLUSIONS

The Fast-Start Plants represent an approach for markets that need combined-cycle power plants operating anywhere from intermediate to continuous duty with frequent start-up and shutdown cycles, without sacrificing base-load efficiency and operability.

This approach goes well beyond conventional measures that have been characterized as industry standards for start-up time enhancements. With the Fast-Start Plant design, the gas turbines have the ability to ramp-up in combined-cycle mode as quickly as in simple cycle mode. The Siemens patented Benson-OTSG is the vehicle that makes this happen.

Special detail in system integration using in-house expertise is key to the success of the plant design. Controlled steam temperatures and an advanced ST start-up mode are considered to mitigate ST induced start-up restrictions. The patented Turbine Stress Controller (TSC) together with a high level of plant automation support the fast starting of both ST and plant while providing a means to vary, monitor and predict service intervals.

The start-up benefits of the Fast-Start Plant have been enumerated with significantly improved start-up times for overnight and weekend shutdowns.

The plant life-cycle costs with the noted savings in NPV make the Fast-Start Reference Power Plant design very attractive. Furthermore this advanced plant represents a new milestone in the sector of fossil-fired environmentally friendly technology with a significant annual reduction in emissions production and water consumption. The Fast-Start Plant retains all of the positive attributes of a typical combined-cycle power plant with the capability for SCR, CO catalyst, duct firing, power augmentation, etc. The additional improvement in operating flexibility is anticipated to ease the permitting and siting process to benefit future power plant developments.

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