Quick and Economical Power Augmentation and Emissions Control Using New Advancements in Combustion Turbine Steam Injection

The Advanced Cheng System^{TM} (ACS^{TM}) is Cheng Power Systems' (Cheng's) proprietary technology for modifying new and existing combustion turbines for steam injection to increase their efficiency and capacity. The ACS^{TM} is a parallel combination of the Brayton cycle and the Rankine cycle. The ACS^{TM} incorporates full-heat-recovery massive steam injection and uses an energy-storage heat-recovery steam generator (HRSG) design that incorporates thermodynamic feedback for automatic control and stable operation at maximum efficiency. The ACS^{TM} has a small plant footprint area relative to a similar-sized combined-cycle power plant. A related product of the ACS^{TM}, the Cheng-BOOST^{TM} system, can be used to provide partial steam injection to increase the capacity of combustion turbines regardless of ambient conditions, usually only up to the limits of their existing electrical-side equipment (generators, step-up transformers, switchgear, etc.). The Cheng-BOOST^{TM} system is especially cost-effective when there is an existing source of steam, such as a simple-cycle cogeneration plant or a combined-cycle plant.

Cheng has also developed a low emission combustion system, the Cheng Low NOx (CLN^{TM}) system, which reduces NOx and CO simultaneously. The CLN^{TM} system uses only steam to control the NOx and CO emissions of combustion turbines, fired boilers and other equipment burning gaseous fuels. No catalysts, ammonia, urea or other reagents, subsystems, or additional equipment are required. NOx levels as low as 5 parts per million on a volumetric dry basis (ppmvd), corrected to 15% O_2, have been achieved with very stable operating characteristics for some combustion turbine hardware, with some experiments achieving levels as low as 3 ppmvd, corrected to 15% O_2. Unlike conventional steam or water injection for NOx control, CO levels are very low, typically in the range of 1 to 5 ppmvd, corrected to 15% O_2. CO levels are often lower when using the CLN^{TM} system than for the unabated combustion turbine. This indicates that the CLN^{TM} system has enhanced combustion efficiency, which is contrary to the effects of other steam-injection or water-injection systems. Efforts are underway to certify the CLN^{TM} system as Best Available Control Technology (BACT) and Lowest Achievable Emissions Rate (LEAR) technology for combustion turbines, boilers, furnaces and other devices.

This paper documents a recent power augmentation and emissions control project that was conceived, implemented and partially completed in Summer 2001. The owners of a major industrial facility in Southern California decided to install the Cheng-BOOST^{TM} system on three existing GE Frame 6B combustion turbines. The decision to modify the Frame 6B engines was driven by the electrical power and natural gas crisis that unfolded in California in the early months of 2001. Table 1 shows the typical performance of the three Frame 6B engines at the beginning of the project. The engines all performed slightly differently, reflecting differences in their vintage and minor differences in their plant configurations.

	A Train	B Train	C Train
Power Output (MW)	32.2	30.9	37.1
Simple-Cycle Heat Rate (BTU/kWh)	12,200	12,400	11,100
Available Process Steam with Duct Firing (pph)	192,000	200,000	230,000
GE Frame 6B Performance Data at the Start of the Project 85°F, 60% Relative Humidity, Inlet Fogging On, 18,000 pph Steam for NOx Control			

Table 1.

The A Train and the B Train of the electrical plant are both GE PG6531B combustion turbines with Mark IV controls, Struthers-Wells HRSGs and Coen duct burners. The units were installed in 1986 and have about 113,500 and 112,000 operating hours, respectively. The C Train is a later model GE PG6541B combustion turbine with Mark V controls, a Deltak HRSG and Coen duct burners. The C Train was installed in 1995 and has about 46,500 operating hours. The performance of all of the engines has been good.

The facility has an electrical load that is fairly well matched with the output of the three Frame 6B units when operating on cooler days in the winter months. The Frame 6B units already have inlet cooling installed. The inlet cooling is effective at providing a power output boost on many days, and with the right ambient conditions, the facility would become a small net power exporter. On warmer days, especially when the humidity is higher, the facility would become a net power importer. The owners are increasing the average electrical power demand of the facility through an ongoing program to electrify some mechanical drive functions. The installation of variable-speed electrical drives improves the overall energy efficiency of the facility, as compared to the use of mechanical drives, but at the cost of a higher electrical demand. The owners were concerned about increasing the electrical demand in an already tight power market that was expected to get tighter and more costly in the summer months. Not only was there concern that the cost of buying additional electricity would be high, but there was also concern that sufficient electrical power might not be available at any price and that electricity supply curtailments would have consequential costs associated with production inefficiencies far in excess of the cost of incremental electricity.

The facility operates the Frame 6B engines in simple-cycle cogeneration mode with a common high-pressure steam header. The steam header provides steam for a number of process functions including heating and the operation of mechanical drives. Several steam turbines with extraction stages are present to supply various steam loads. The steam demand for the facility is generally higher in the winter than in the summer, and the total steam demand ranges from about 750,000 pounds per hour to about 900,000 pounds per hour, depending upon ambient temperature and the product mix that is being produced at any particular time. Auxiliary boilers balance the steam load with the output of the simple-cycle cogeneration plant. With the electrification of some of the mechanical drives, the amount of steam required is decreasing, while the peak electrical demand for the facility is increasing. Future capacity increases and changes in product mix, however, will increase the total steam demand under some conditions, so the owners also wanted to maintain flexibility with regard to varying steam and electrical power production.

The owners decided that they wanted the facility to be electrically self-sufficient under peak summer conditions. Furthermore, they wanted to add some additional capacity to meet increased future electrical demand as the electrification projects progressed. Adding 25 to 35 additional MW of electrical generating capacity was targeted in order to meet projected peak demand requirements for the next few years. Table 2 shows some of the options that were available to the owners. Diesel generators were ruled out because of their high capital cost, large footprint, relatively long delivery time and difficulty in permitting. Natural gas reciprocating engines were ruled out on much the same basis, though they might have been somewhat easier to permit. A small combustion turbine was ruled out mostly due to its cost and long lead-time. Secondary considerations were the smaller engine's lower expected net electrical efficiency and relatively large footprint – there is space available for only one additional combustion turbine at the site, and a small engine would use it less efficiently than a larger one. A larger combustion turbine, specifically a fourth GE Frame 6B, was the option preferred by the owners, but its cost and long lead-time made it impractical as a near-term solution. The Cheng-BOOST™ system provided the best alternative given the owners' constraints. The Cheng-BOOST™ system could provide the desired electrical capacity increase under all ambient conditions, would not change the plant's footprint, would be low-cost and could be installed in time to impact current year operations. Perhaps as important, the Cheng-BOOST™ system would not change the equipment description in the plant's current operating permits – the A, B and C Trains would remain steam-injected combustion turbines operating within the existing permitted heat release rates and emissions levels.

	Foot Print	**Delivery Time**	**Permitting**	**Efficiency**	**Cost**
Diesel Generators	Large	Long	Difficult	Medium-High	High
Natural Gas Reciprocating Generators	Large	Long	Moderate	Medium	High
Small New Technology Combustion Turbine	Medium	Long	Moderate	Medium	Moderate
Large New Technology Combustion Turbine	Medium	Long	Moderate	Medium-High	Moderate
Cheng-BOOST™	None	Short	Easy	Medium	Low
	Potential Options for Adding Additional Electrical Generating Capacity at the Facility				

Table 2.

Table 3 shows the projected performance on which the project was based for each of the A, B, and C Trains with the Cheng-BOOST™ system installed. For all three engines combined, the project provides a projected total electrical capacity increase of about 25.8 MW under the same conditions as the base plant performance figures in Table 1. Total steam injection rate is about 236,000 pounds per hour for all three engines combined, but the net steam consumed by the modifications to achieve the indicated power increase is only about 70% of this amount, because the injected steam provides additional heat recovery capacity to the HRSGs in excess of that provided by the simple-cycle combustion turbine exhaust flows. Another way to state this is that the net reduction in available process steam at the nominal operating conditions is only 170,000 pounds per hour, even though a total of 236,000 pounds per hour of steam are being injected into the engines. The injected steam increases the total mass flow of the exhaust and the total exhaust gas mixture heat capacity, which combine to increase the total amount of heat transfer available as a function of the tight pinch-point design of the HRSGs. This characteristic makes the Cheng-BOOST™ and CLN™ systems very efficient steam users that can provide the desired output increases and emissions reductions with minimal impact on plant process steam requirements.

	A Train	B Train	C Train
Power Output (MW)	42.0	42.0	42.0
Cheng-BOOST™ Heat Rate (BTU/kWh)	10,700	10,600	10,400
CLN™ and Cheng-BOOST™ Steam Injection Rate (pph)	95,000	110,000	58,000
Available Process Steam with Duct Firing (pph)	137,000	125,000	202,000
GE Frame 6B Performance Data after Cheng-BOOST™ 85°F, 60% Relative Humidity, Inlet Fogging On			

Table 3.

Although the outputs of the modified Frame 6B combustion turbines are being limited to 42 MW to comply with the existing plant air emissions permits, an analysis of the electrical side of the plant indicates that each engine might make up to 46 – 47 MW over the typical range of ambient conditions. These power levels can be realized by increasing the steam injection rates, and operation at these power levels is within the capabilities of the Cheng-BOOST™ system that was installed. It is also possible to increase the steam production of the HRSGs to provide for a larger power boost and to expand the operating envelope of the plant by adding supplemental air and increasing the size of the duct burners, but this was not part of the initial project. The CLN™ system can be incorporated into the duct burners to increase their firing rate while simultaneously reducing NOx and CO emissions. Modifying the plant permits and increasing supplemental firing may be the subject of a future project to increase electrical output while meeting larger process steam demands.

Figure 1 shows the basics of the steam injection techniques for the Cheng-BOOST™ and CLN™ systems in a simple representation of a Frame 6B engine combustor. For the Frame 6B engines, steam is injected with the fuel via a special fuel nozzle, through a manifold that encircles the combustor can and into lances with nozzles directed into the combustor liner air dilution holes, and through a combustion wrapper nozzle that provides cooling steam to the turbine first-stage nozzles. The design and positioning of the steam injection hardware and the quantity, quality, temperature and pressure of the steam at each injection location are proprietary and are precisely tailored to yield the desired results. These methods of steam injection are key distinguishing characteristics between the ACS™, the Cheng-BOOST™ system, the CLN™ system and conventional STIG. These methods of steam injection enable the stable flame characteristics, low noise and vibration, low air pollutant emissions, acceptable pressure ratios and parts lives, high efficiency and high output that are achieved at the steam mass flow rates used in Cheng's technologies.

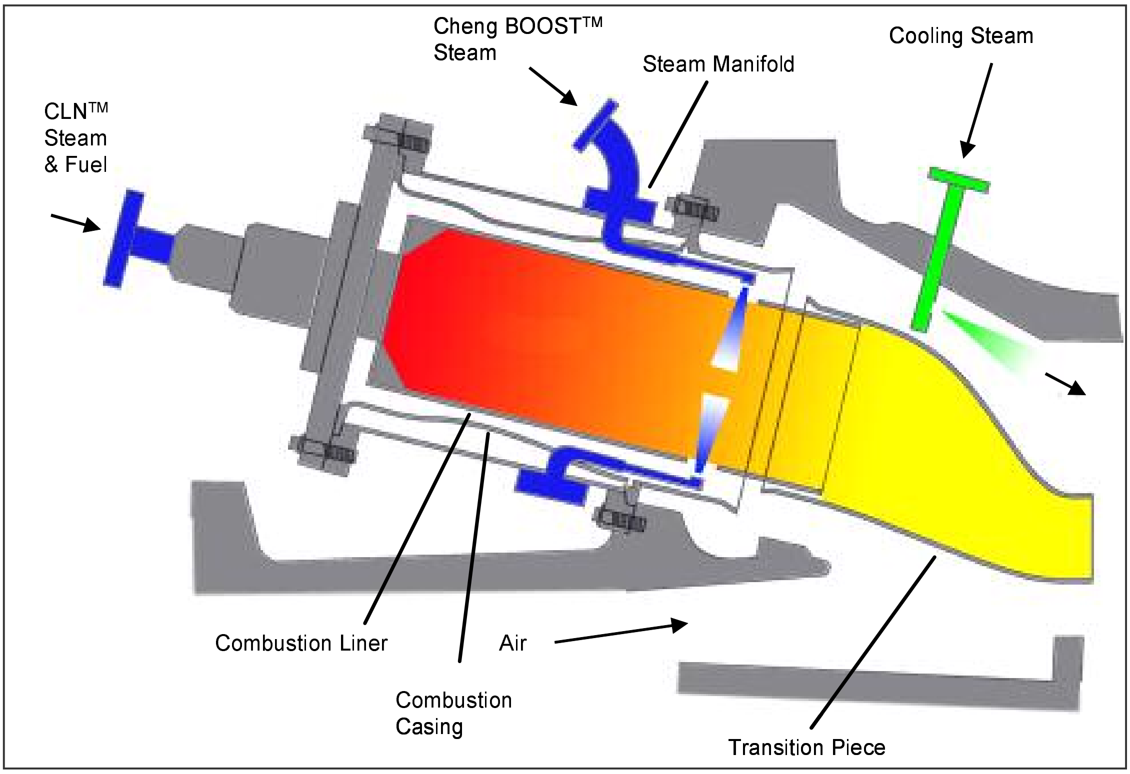

Figure 1. Typical Retrofit for GE Frame Engine Combustors

The CLN™ system is a patented process developed by Cheng for combustion turbine emissions control. Unexpected phenomena that were observed during combustion turbine steam-injection testing led Cheng to carry out an in-depth program focused on understanding the fundamental mechanisms of NOx formation. CLN™ is a combustion technology that simultaneously reduces NOx and CO emissions in a diffusion flame. The CLN™ system precisely meters and mixes steam at specified conditions with fuel gas and sends the steam-fuel mixture to specially-designed fuel nozzles. The CLN™ nozzle design increases the momentum of the fuel jets, but not the fuel flow rate, and the system uses special mixing equipment to homogenize the fuel with the steam. The higher fuel jet momentum of the CLN™ system flame enhances the diffusion rate of oxygen towards the flame front. The CLN™ system also reduces the nitrogen concentration at the flame front by the counter-diffusion of a water vapor flux. One of the unique features of the CLN™ system is the mixing of the steam into the fuel rather than into the combustion air. The benefit of diluting the fuel rather than the air is that the diluents do not oppose the flux of the combustion products. Also, diluting the fuel and increasing the fuel jet momentum causes the flame front to move closer to the fuel jet. As a result, the temperature gradient in the flame increases, which breaks down the fuel faster, and the diffusion rates and concentration gradients of the combustibles increase, which increases the combustion rate. These changes in flame kinetics produce a smaller flame for the same heat release rate with a more uniform temperature distribution, lower peak temperature and shorter residence times for N species, all of which inhibit NOx formation.

Figure 2 shows several two-dimensional false-color images of a methane (natural gas) flame under the full-load operating conditions found in a Westinghouse 501-D5 combustion turbine combustor. The color scales correspond to the mass fraction or concentration of CH_4, NO and CO and the absolute temperature of the flame structure, as indicated in each part of Figure 2. The upper-left quadrant of the figure shows the CH_4 concentration, which essentially defines the flame boundary since combustion completes when all the fuel is consumed. Notice how much the flame envelope shrinks with the CLN™ system. The upper-right quadrant of the figure shows the temperature profile in the combustor. Notice that there is a significant lowering of the peak temperature with the CLN™ system, but also important is the fact that the hottest regions in the combustor are much smaller. The lower-left quadrant of the figure shows the dramatic impact that the CLN™ system has on NOx production. Not only is the maximum NOx concentration greatly reduced, but again, the size of the active NOx forming regions are also much smaller with the CLN™ system. Finally, the lower-right quadrant of the figure shows the concentration of CO in the flame structure. In this case, the regions in which CO is present in significant concentrations are much smaller, and the peak CO concentration is lower.

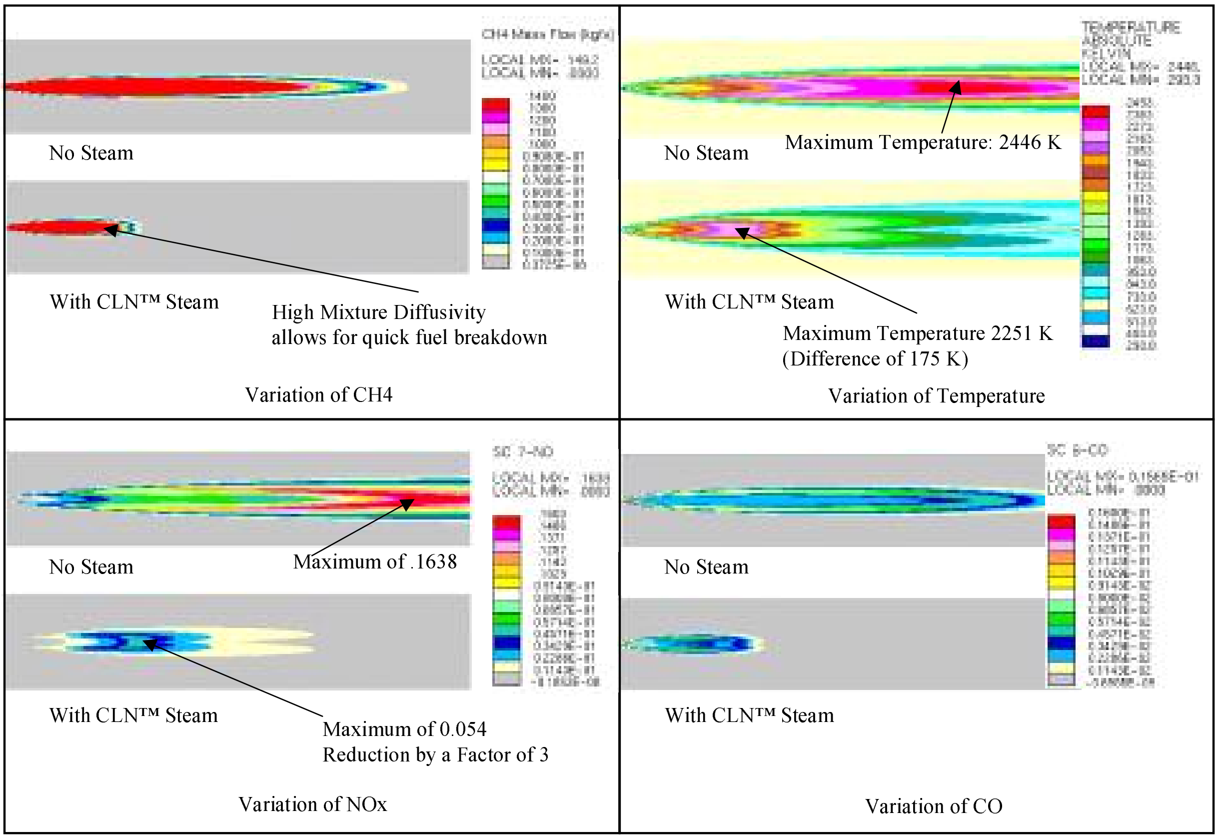

Figure 2. W501-D5 Combustor Flame Characteristics Under Full Load Conditions

The CLN™ system has been the subject of extensive research and development. In addition to numerous laboratory bench-scale tests and demonstrations, the CLN™ technology has been extensively modeled using the most sophisticated computation resources available. Cheng uses the STAR CD V. 3.10 computational fluid dynamics software with the ICEM CFD meshing program and the N-Step combustion kinetics model to simulate the CLN™ technology. Among hundreds of available mechanisms, Cheng chose to separate out for its calculations the 28 most prominent reaction steps among the combustion reactions for all the species C_xH_y, H_2, CO, N_2, etc. present in the flame. Simulations have been run that incorporate as many as 500,000 cells. Cheng has also invested heavily in an extensive test facility that enables the full-scale, live-fire testing of actual combustion turbine hardware. The test facility uses an Allison 501- KH version of the original Cheng Cycle to provide steam for injection into the CLN™ and Cheng-BOOST™ test hardware. A schematic of the test facility is shown in Figure 3. The test facility allows a single combustion turbine hardware set, consisting of the combustor can, combustion liner, flow sleeves (if applicable), transition piece, combustor endplate and fuel nozzle, along with the appropriate Cheng hardware, to be tested.

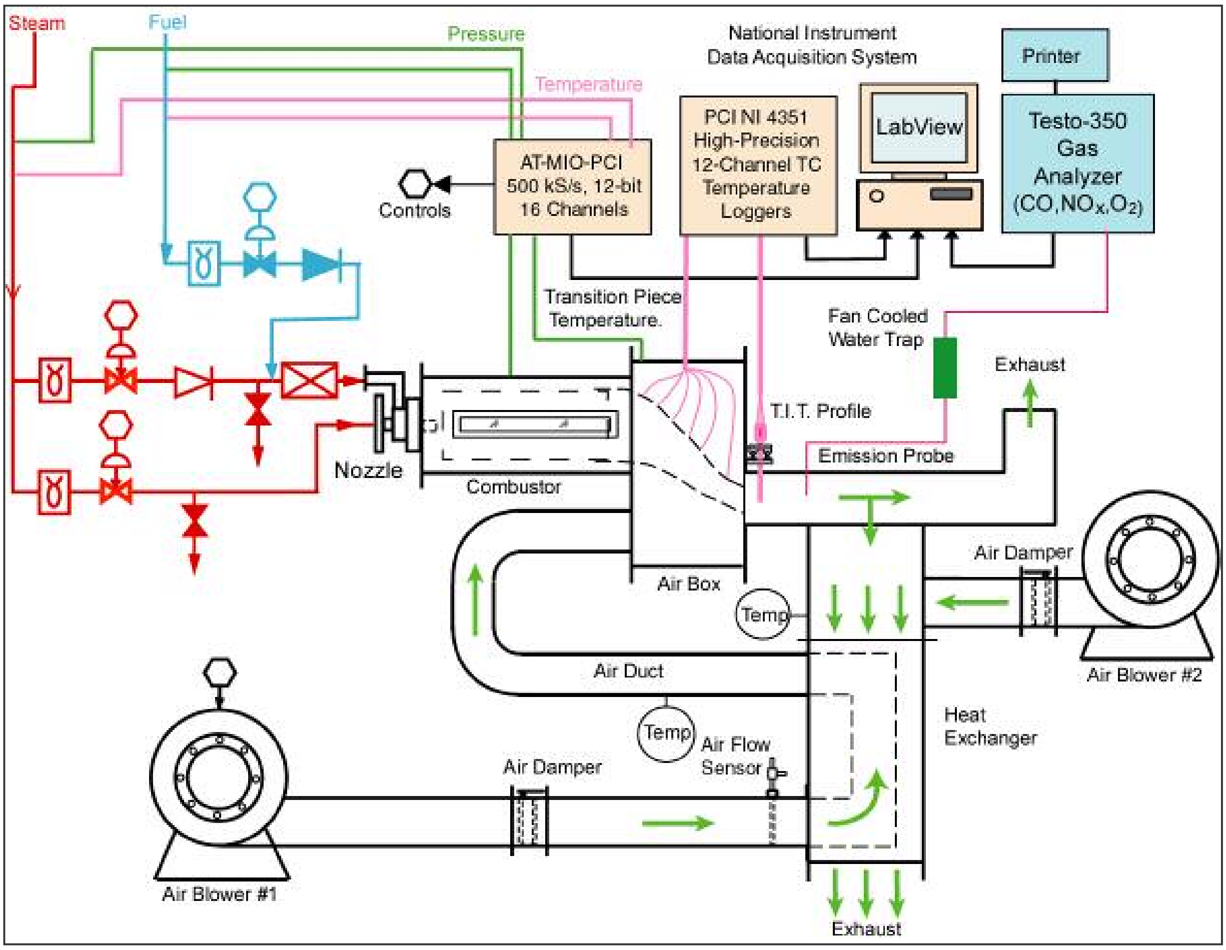

Figure 3. Cheng's Combustion Turbine Hardware Test Rig Schematic Diagram

Figure 4 shows the exhaust portion of the test rig during a test firing of the Westinghouse 501-D5 hardware. The impressive heat-release rate that results from the full-scale testing of a single-combustor is clearly visible. Figure 5 shows a close-up of an interesting feature that has been incorporated into the test rig, a window to allow optical imaging of the flame during operation. Figure 5 shows the actual flame conditions in the vicinity of the downstream dilution air holes in the combustion liner during one of the Westinghouse 501-D5 tests. The qualitative affects of steam injection on the flame size and temperature, as evidenced by its luminosity and the heating of the edge of the liner dilution air hole, are clearly visible.

Figure 4. Cheng's Combustion Turbine Hardware Test Rig Exhaust During Operation

Figure 6 is a generic P&ID for typical combustion turbine CLN™ and Cheng-BOOST™ system installations. The configuration shown is similar to that which was used on the three Frame 6B engines. The standard P&ID assumes that an engine will be modified to accept three steam sources, CLN™ steam; Cheng Augmentation System (CAS) steam, which is common to both the Cheng-BOOST™ system and the ACS™; and cooling steam. It also assumes that steam is supplied from an HRSG with a superheater and that one main steam line feeds the three steam lines. In the case of the Frame 6B engines, the HRSGs were tapped in the vicinity of their connections to the facility main process steam header. The nominal steam conditions in the main process steam header are 915 psia and 720° F. Steam from the HRSG goes through an external moisture separator to remove any water droplets and to achieve the required steam purity. The main steam line is then split into three streams. For the CLN™ steam, saturated steam is mixed with superheated steam to achieve the desired degree of superheat. In a system with saturated or

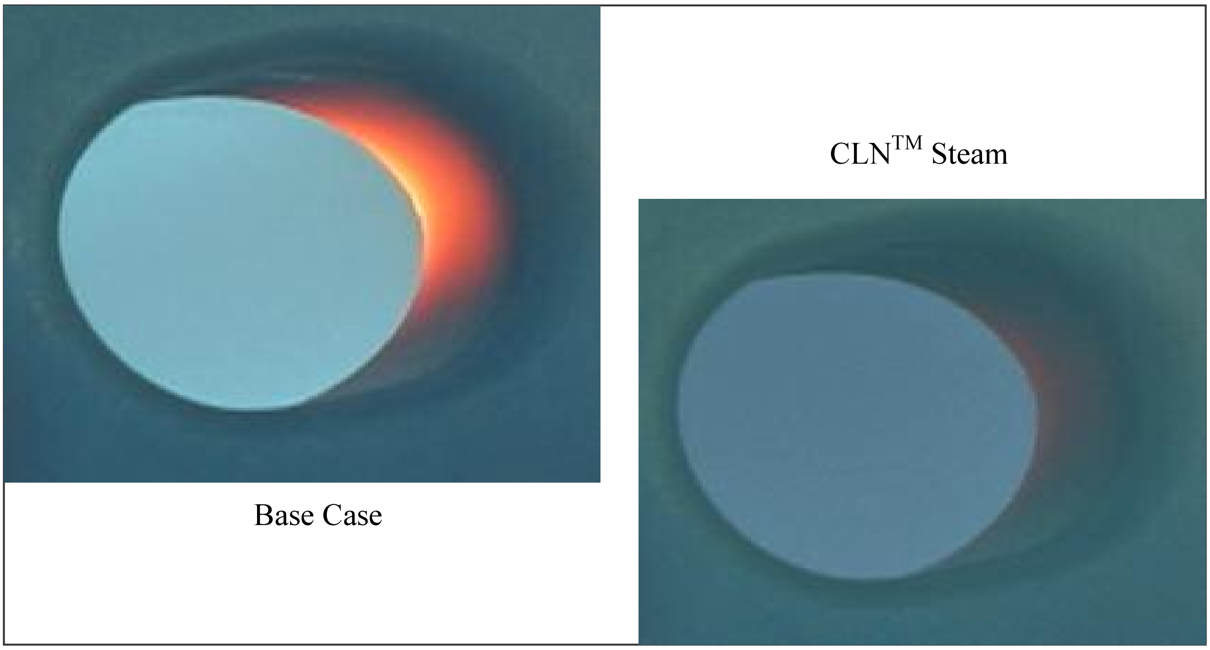

Figure 5. Westinghouse 501-D5 – Comparison of the Downstream Dilution Hole During Testing.

slightly superheated steam, the CAS steam that supplies the Cheng-BOOST™ system goes through a superheater to raise the steam temperature. The outlet temperature is controlled by the three-way bypass valve, which controls the amount of superheat and the resulting temperature of the steam-fuel mixture. A fixed orifice regulates cooling steam flow. Automatic drain valves, purge valves and bypass valves block steam flows, drain condensate and pre-heat the system during startup to ensure that only dry steam with the proper parameters is introduced into the engine. Pressure reducers, drag valves or attemperators are incorporated into specific installations depending upon the steam sources and supply conditions available, and these are not shown on the generic P&ID. Inputs to and outputs from the ACS™ control system are shown as hexagons on the P&ID. The control system provides sequencing for start-up and shutdown functions, as well as for normal plant control.

Figure 7 shows the original, very optimistic project schedule for Cheng-BOOST™ system installation. Unfortunately, the schedule was not achieved, even though it was basically sound, due to a variety of factors. Long-lead-time items, such as control valves and instruments, proved more difficult to get than was anticipated when the schedule was developed. In many cases, it took as long as 12 weeks to get some of the valves and instruments that were needed. Also, there were some fabrication issues with the custom-designed Cheng hardware, and several prototyping cycles were needed to perfect the design for manufacturing. In the end, only the B Train was completed in October 2001. The A Train and the C Train were deferred until scheduled outages in early 2002. The B Train could possibly have been completed with weekend outages only, but because of the overall slip in schedule, it was completed in a single outage. Subsequent short outages were needed to optimize its performance. Now that the fabrication issues for the proprietary parts have been resolved, the original schedule can be met

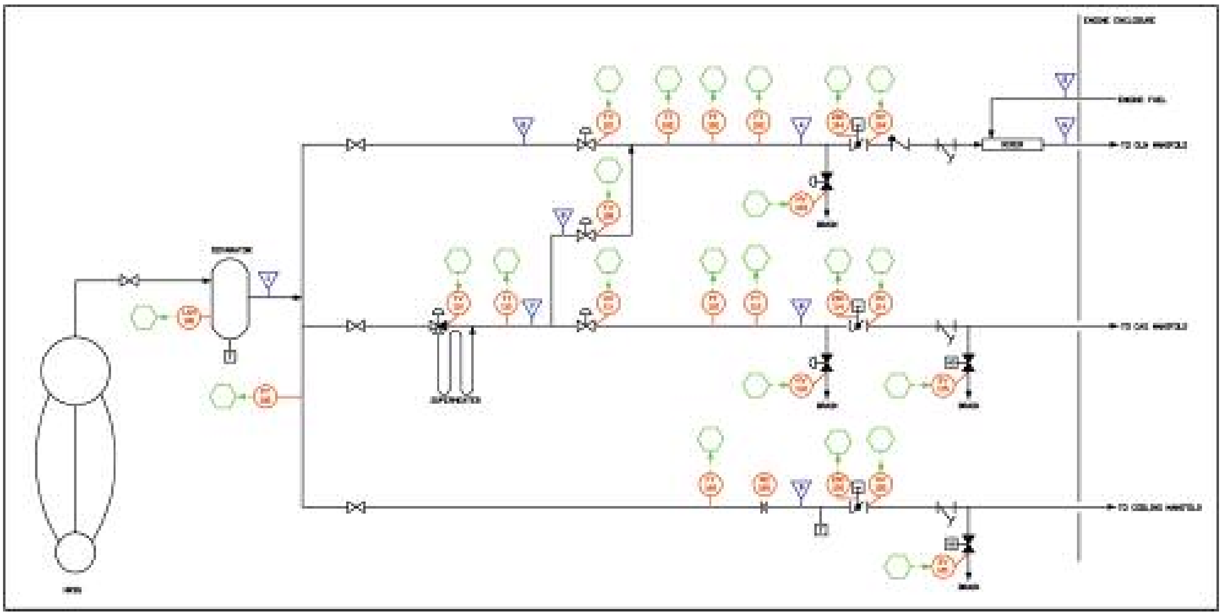

Figure 6. Generic P&ID for ACC^{TM}, Cheng BOOST^{TM} and CLN^{TM} Installations with Existing HRSG

with better availability of control valves, instruments and PLCs. Cheng is taking some of this equipment into inventory to enable a faster response time.

Figure 8 shows one of the steps in the fabrication of the Frame 6B combustor cans. Hickham Industries, Inc. of Houston, Texas, a Cheng partner, fabricated the combustion turbine parts for the Frame 6B engines and did the on-skid installation work. Local mechanical, electrical and instrument and control contractors that already had service agreements with the owners

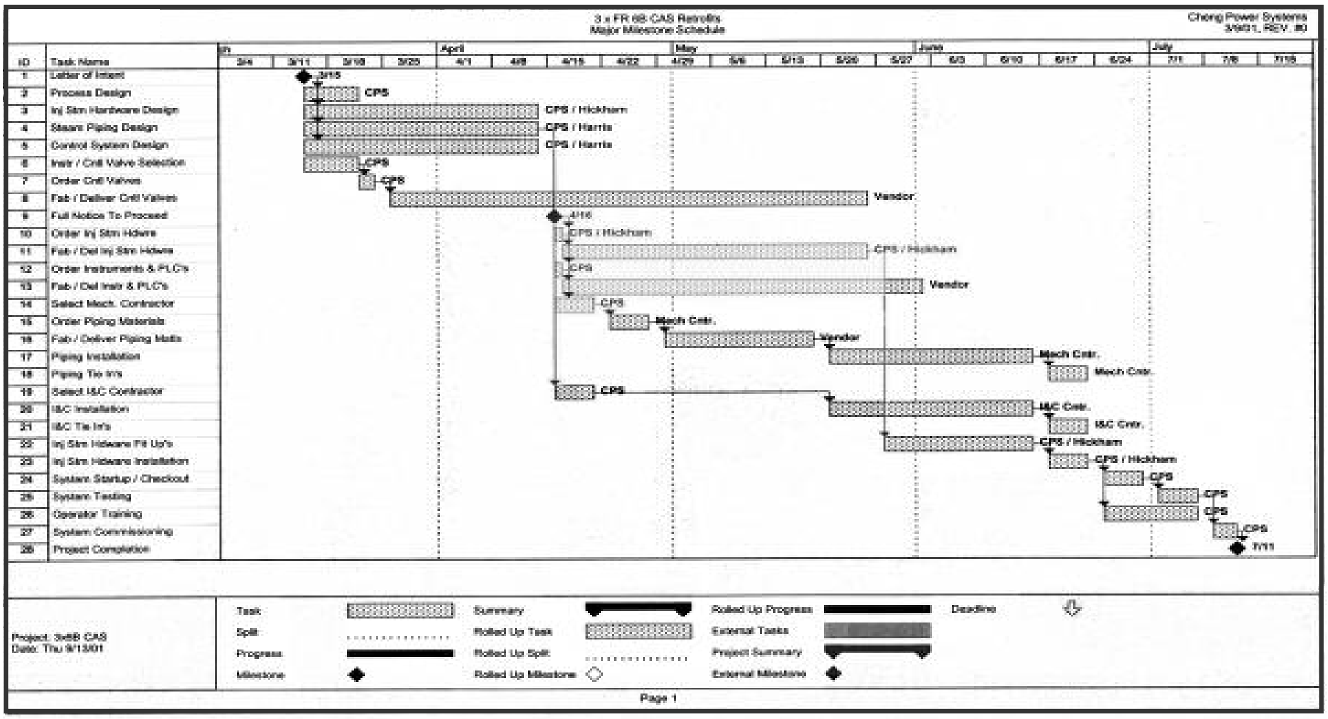

Figure 7. Initial Overall Project Schedule

performed the balance of plant installation and construction work. Harris Group, Inc. of Denver, Colorado, another Cheng partner, did the balance of plant engineering and the detailed design and construction drawings, including piping isometrics and point-to-point connection diagrams. Figure 9 shows a CLN™ system and Cheng-BOOST™ system Frame 6B combustor can in the test facility before installation on one of the plant engines. Figure 10 shows a close-up of the combustor with some of the CLN™ system and Cheng-BOOST™ system hardware installed. The belt manifold and the four nozzles that meter steam and air into the combustion liner dilution holes are clearly visible. Figure 11 is a photograph of some of the installation work on one of the engines.

The B Train was first operated with Cheng steam injection on September 16, 2001. The startup was uneventful, but the initial performance of the engine was not as good as expected. A flow restriction was encountered in the system that limited the amount of steam that could be mixed with the fuel. The flow restriction was diagnosed as a poorly designed fuel nozzle, and a shutdown for replacement and system adjustment was scheduled for the weekend of September 29, 2001. Table 4 shows the measured performance of the B Train following this outage. The performance was still not optimum due to limitations in the amounts of Cheng-BOOST™ steam that could be supplied, but it was very satisfactory. Remedies for these concerns were identified, and final corrective actions were deferred to a future outage. Under the revised project schedule, the A Train and the C Train were not scheduled to start until 2002, so performance data for them could not be included. Performance test data for the A, B and C Trains will be available by request from Cheng as it becomes available. It is important to note that with the CLN™ system and Cheng-BOOST™ system, the simple-cycle combustion turbine operating characteristics are not permanently altered by the modifications, and the nominal simple-cycle power output is available without steam injection exactly the same as for an unmodified combustion turbine. Steam can be diverted to or from process requirements as necessary to match process loads or to increase power outputs up to some plant limit, such as gearbox torque, or generator or step-up transformer temperature rise. Some minimum level of CLN™ steam is required to maintain any particular emissions level, though the amount of steam used in the CLN™ can be reduced to zero, if unmitigated emissions are allowable. The ACS control system injects steam to augment power production to a particular level, to control emissions to a particular level or to match process steam demand with not to exceed power and emissions levels.

	Actual Base-Load No Steam	**Project Design**	**Actual Base-Load With Steam**
Power Output (MW)	29.5	42.0	41.1
Cheng-BOOST™ Heat Rate (BTU/kWh)	13,034	10,600	10,739
Total Steam Injection Rate (pph)	0	109,984	107,100
GE Frame 6B Performance Data after CLN™ System and Cheng-BOOST™ Inlet Fogging On			

Table 4. B Train Performance Data Comparison on October 5, 2001, with Cheng-BOOST™ Steam Following Second Outage

The total cost to install the Cheng-BOOST™ system on all three Frame 6B engines will be $6.1 million. This expenditure will purchase a minimum 25 MW increase in electrical output on a "nominal" 85^{o} F day with 60% relative humidity, which equates to a cost for power augmentation of only $244 per kW. Through permitting changes only, the potential exists to raise the total electrical output gain for all three engines from 25 MW to up to 37 MW. The only "cost" for these benefits is about 158,000 pounds per hour of process steam under the "nominal day" conditions, steam that was already in surplus during some parts of the year, and which could be readily generated with the installation of increased duct firing and, possibly, supplemental air. Depending upon the spark-spread, the cost of this process steam could be more than offset by additional peak electricity sales or reduced electricity purchases, making this retrofit very capital-efficient peaking capacity.

The CLN™ system and the Cheng-BOOST™ system have proven to be fast to implement, economical to operate, cost-effective and reliable ways to increase the electrical output and to lower the emissions of combustion turbines that have a small steam supply available. The CLN™ system and the Cheng-BOOST™ system work equally well whether the steam is from a nearby steam electrical generating plant or fired boiler, or from an HRSG operating in simple-cycle cogeneration or combined-cycle mode.

Figure 8. One of the Steps in the Fabrication of the Frame 6B Combustor Cans

Figure 9. A Modified Frame 6B Combustor Being Tested at CPS

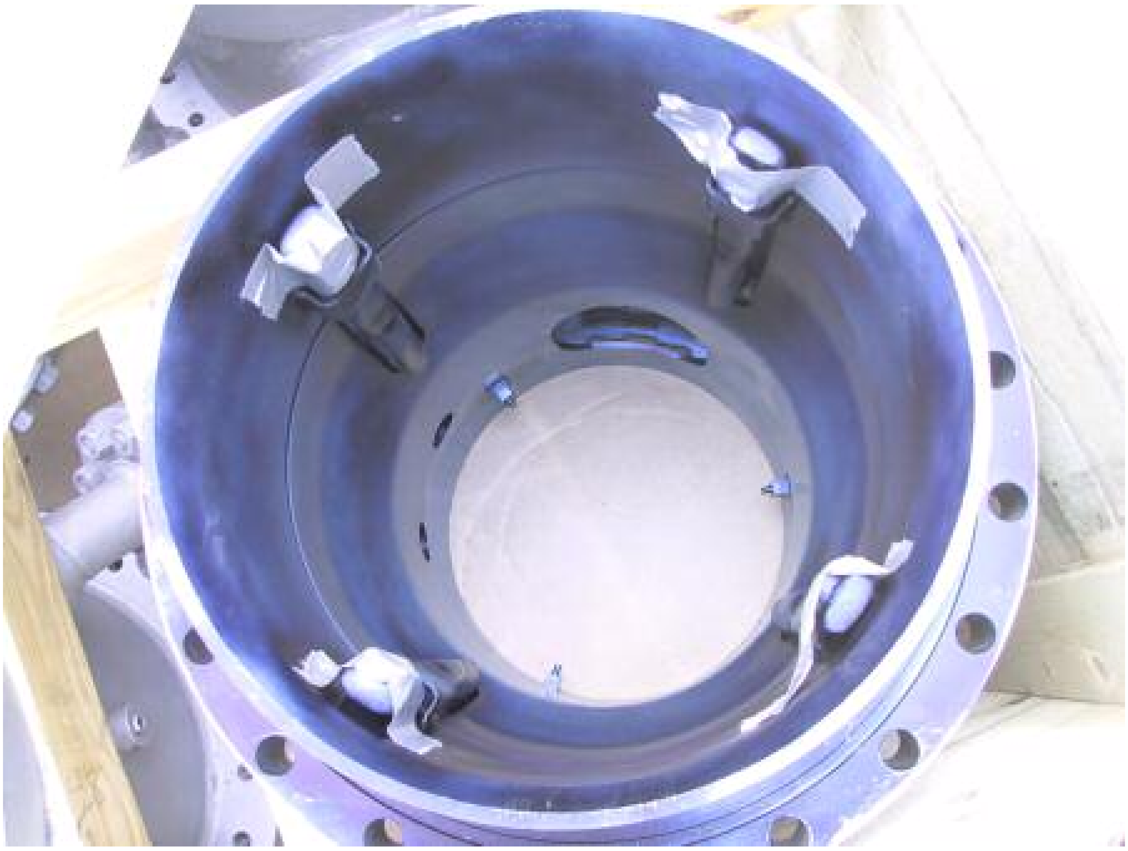

Figure 10. Close-up of the Modified Frame 6B Combustor

Figure 11. Modifications in Progress on One of the Frame 6B Combustion Turbines