International
Power Technology

# SUMMARY OF

# IPT CHENG CYCLE COGENERATION

# TECHNOLOGY and KNOW-HOW

March 1987

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with IPT Staff

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## INTRODUCTION

At International Power Technology, "technology" has always been much more than just a part of our name. The company was founded in October 1974 on the basis of a core of technology which has grown and evolved continuously since then. Technology and technological expertise have been key elements in attracting investors and talented employees, establishing an extensive patent structure, creating strong vendor relationships, and providing product recognition, reliability, and competitiveness.

IPT has developed technological know-how in several applications areas including microporous permselective membranes, specialty fabric coatings which are both breathable and waterproof, thermal membrane desalination for the production of fresh water from waste heat, limestone-free scrubbing of sulfur dioxide from stack gases, and high-recovery diffusers. However, the largest block of technological growth has been in optimized steam-injected gas turbine engines and their subsequent development into high-efficiency generation and cogeneration cycles. This report summarizes the scope of IPT's technology and know-how in this latter area.

## METHODS and SOURCES

IPT's technology and know-how are derived from many sources. Computational models are developed and executed on IPT's in-house computers. IPT owns and operates its own prototype shop and fabrication facilities in support of experimental programs, both for IPT directly and for IPT's vendors. IPT has designed, instrumented, and operated its own small-scale engine test cells and laboratory facilities for basic research, product development, pilot testing, and product support. Technological development includes drawing on the expertise of well-recognized consultants, many of whom have provided their specific talents to IPT for over ten years.

IPT often adds supervision and/or key engineers to the efforts of IPT's vendors in resolving design, production, and maintenance problems. IPT staff provides the design basis and key equipment specification for the Cheng Cycle Series 7 cogeneration plant modules and oversees their manufacture and factory test via IPT's vendors. The entire scope of controls and instrumentation for the Series 7 product is IPT's direct responsibility including algorithm development, software installation, and system startup.

IPT participates in and/or directs the installation, commissioning, and acceptance testing of its cogeneration plants. IPT is also directly responsible for the day-to-day operation, maintenance, and upgrade of several cogeneration plants incorporating IPT-supplied equipment; this provides direct feedback to the design staff and an opportunity to conduct field performance and evaluation programs.

These various paths of know-how development, which cover the full spectrum of development and application, are combined to produce an interlocked and well-rounded technology base.

## CHENG CYCLE OVERVIEW

The concept of gas turbine steam injection is not new; experiments have been performed as early as 1905. Until recently however, use of steam injection had been limited to $NO_x$ control and/or simple power augmentation. The critical and interrelated nature of steam-to-air ratios, steam-to-fuel ratios, and other cycle parameters in optimizing the efficiency of the steam injected gas turbine cycle was first realized by Dr. Dah Yu Cheng, a professor at the University of Santa Clara. In 1974, Dr. Cheng formed International Power Technology to develop and commercialize what is now called the Cheng cycle. Since that time IPT has been granted or has pending over 50 US and international patents on the concept and associated hardware.

The Cheng cycle combines the Brayton (gas turbine) and Rankine (steam turbine) cycles in a unique parallel manner. Traditionally, the Brayton and Rankine cycles have been "sequentially combined" by cascading them in series, as in the well-known combined cycle. In both combined cycle and in Cheng cycle, engine exhaust heat is used to generate superheated steam in a waste heat recovery boiler. In the combined cycle, this steam is expanded through a steam turbine to a condenser, producing additional work without consuming additional fuel.

In the Cheng cycle, this superheated steam is injected into the gas turbine itself. The choices of injection location(s) and injection geometry are made so as to balance the theoretical cycle potential and the practical constraints of the specific engine involved. This steam may be further heated in the engine and then, being mixed with the Brayton cycle air, expands through the turbine producing additional work from the same rotating equipment. The injected steam produces power in parallel with the air of the gas turbine, thereby combining the Brayton and Rankine cycles. The boiler captures otherwise wasted energy from both the steam and the air in the gas turbine's exhaust.

For a given gas turbine greater in size than 15-20,000 horsepower, both Cheng cycle and combined cycle improve the power output and heat rate by a comparable amount. However, Cheng cycle's "parallel" combining is achieved without requiring the combined cycle's steam turbine, additional generator, condenser, cooling tower, and auxiliary equipment. For smaller engines, combined cycle derivations suffer from poor steam turbine efficiencies and disproportionate complexity associated with the added equipment. Cheng cycle does not suffer these drawbacks and has been successfully applied to engines as small as 45 horsepower.

Dr. Cheng discovered that peak cycle efficiency occurs at a specific mass flow of superheated steam to the gas turbine. The Cheng cycle patents describe how the optimal waste heat boiler design is intrinsically tied to the cycle pressure ratio and turbine inlet temperature of the gas turbine. Briefly, the design principle is that insufficient flow of steam to the gas turbine results in excess energy exhausted to the atmosphere in the form of sensible heat. Too much steam flow to the gas turbine results in excess energy rejected to the atmosphere in the form of latent heat of vaporization. Unless these two forms of heat rejection are correctly balanced, efficiency declines (although in the latter case *power output* is further increased) when compared to the peak efficiency point.

## CHENG CYCLE COGENERATION

In a pure power application of the Cheng cycle, all the steam produced by waste heat is recycled through the gas turbine. The single form of useful output from the cycle is electricity (or shaft power). The Cheng cycle concept is readily adapted to cogeneration applications wherein there are simultaneously two useful forms of energy output from the cycle: shaft power or electricity as well as productive thermal output (generally steam and/or hot water) which is delivered to an external process.

For cogeneration applications, the Cheng cycle system is modified to the extent that steam may be used for process needs and/or sent to the gas turbine. In addition, a duct burner is added between the gas turbine and the waste heat boiler to increase the total steam producing capability of the system. The added steam may be used for increased process loads or for injection into the gas turbine and increased power output. Unlike a simple gas turbine applied to cogeneration, Cheng cycle follows process thermal load variations without cycling the turbine firing temperature; instead, the turbine mass flow and/or the duct firing rate is what is varied to accommodate process load swings. In addition, the two forms of energy output can be varied independently of each other. The overall result is a cogeneration system which provides both operating flexibility and mechanical simplicity.

## SERIES SEVEN PRODUCT

The first commercial development of the Cheng cycle concept for cogeneration applications is called the Cheng Cycle Series 7-Cogen. It is based on the 501-K industrial gas turbine, modified and manufactured for Cheng cycle operation by Allison Gas Turbine, a Division of General Motors. At its current stage of development, the system is capable of producing up to 5.6MW of electricity and 44,000 lb/hr of process steam. The Cheng Cycle Series 7-Cogen has accumulated over 55,000 fired hours of operation at five locations in the USA.

The Cheng cycle system consists of pre-engineered, modular, component groups: a gas turbine generating set, a matched heat recovery steam generator, a two-level boiler auxiliaries skid, and system controls responsible for coordinating and optimizing operation of the complete system. The flexibility of the system makes it applicable to a wide range of sites with little or no design change required of the major equipment package.

Technical suitability and proven reliability were primary reasons for choice of the 501-K. The engine's compressor surge and structural design margins make it ideal for the increased mass flow and power output associated with Cheng cycle operation. In addition, the 501-K has a large installed base of industrial, marine, and aircraft applications, and is supported by a well-developed service industry. Development of the steam-injected 501, designated the 501-KH, has been a cooperative effort between IPT and Allison Gas Turbine.

The heat recovery steam generator (HRSG) is very similar to a conventional waste heat boiler with one exception: the addition of a superheater upstream of the evaporator section. Peak generation efficiency is enhanced by the controlled ratio of surface areas between the superheater and evaporator. The Series 7 is configured for supplemental firing, which greatly enhances the operating flexibility of either Cheng cycle or standard turbine cogeneration plants. The HRSG is produced by major boiler manufacturers to IPT's specification under subcontract to IPT.

The control system coordinates the overall operation of the system to ensure that the plant operates in the most economic and reliable manner. The control system can be thought of as operating on two levels:

A supervisory level which, in conjunction with the operator, coordinates overall operation on a real time basis. Decisions at this level are made on the basis of economic optimization, taking into account the performance characteristics of the system and current energy prices. This level also supports detailed reporting functions regarding system performance.

A functional level which controls the physical parameters of the plant components (fuel flow, steam flow, etc.). This level implements the operating strategy chosen at the supervisory level and ensures that process requirements are met at all times within the safe operating envelope of the hardware.

The Series 7 control system utilizes distributed digital hardware configured to meet the needs of the Cheng cycle cogeneration system, as well as the balance-of-plant equipment, and any site specific requirements.

# CHENG CYCLE TECHNOLOGY

This summary of Cheng cycle technology and know-how focuses on IPT's development and initial application of the Cheng Cycle Series 7-Cogen product. As one would expect, the total scope of technology contained within the Series 7-Cogen includes anterior developments throughout all of the components and subsystems which make up the product. This exhaustive background of technology is not discussed; it is arbitrarily taken for granted. Hence, this report outlines technology and know-how which has been recently developed, which was required by the cycle concept itself, which was triggered by combining subsystems, or which resulted from the requirements of the product's intended use.

While most of the items discussed are applicable to generic, steam-injected gas turbines, a significant portion of the technology results from applying IPT's expertise to the specific adaptations required of the Allison 501-K engine and the unique requirements of the cogeneration market. Finally, although many of the ideas discussed are also the subject of one or more IPT patents, they are included to show specific examples of IPT's technology applied to a particular product.

Cheng cycle technology has evolved in three distinct layers:

**ENGINE/GENSET** - the innermost layer, which focuses on the gas turbine engine and its supporting subsystems. In addition to the engine, this layer includes the main reduction gear, generator, starter, skid, genset enclosure, lubrication and combustion air systems, and a portion of the distributed digital control system.

**HRSG/CYCLE** - the middle layer, which adds the matched HRSG to the genset, completing the core Cheng cycle hardware. Included here are the transition duct, superheater, duct burner, evaporator, economizer, feedwater heat exchanger, deaerator, steam purity control equipment, boiler auxiliaries, and a portion of the control system.

**PLANT/ENVIRONMENT** - this outermost layer adds the balance of plant systems and several other features which tailor the Cheng cycle for successful operation in a cogeneration environment. Examples include the water treatment system, fuel(s) preparation equipment, switchgear and protective relays, economic operating strategies, performance monitoring systems, and the remainder of the control system, including the operator interface.

Distinct from the above three layers, there are additional areas of know-how development which unify these three layers into a cohesive product:

**INSTRUMENTATION AND CONTROLS** - IPT has implemented a distributed digital control system based on the Bailey *NETWORK 90*^tm^ hardware. The result is a unified approach across all three layers to both sequential and real-time control, as well as support for the important functions of monitoring, reporting, trending, and archiving.

**INTEGRATION AND PACKAGING** - IPT streamlines plant installation by pre-packaging and testing all equipment in logical modules. This provides for uniform equipment interfaces, reduced construction time, and standardized plant layouts.

**OPERATIONS AND MAINTENANCE** - The technology behind the Series 7-Cogen product has been extended to include many of the real-life requirements which are often over-looked in a less well-developed collection of equipment. Included are proven operating, diagnostic, and maintenance procedures as well as specific hardware and software which enhance operations and maintenance.

An additional characteristic of the developed know-how results from IPT's "full service" approach to the cogeneration market. IPT's various divisions are involved with the entire cogeneration environment including project development, financing, equipment supply, plant construction, plant management, plant ownership, and plant operation. Although the methods are not discussed in detail here, each division provides a rich source of feedback, contributing to the overall maturity, strength, and practicality of the technology.

## ENGINE/GENSET TECHNOLOGY

Much of the technology in this layer addresses adaptations required of a gas turbine engine when applied to Cheng cycle operation. In this case, the base engine is the Allison 501-KB5, an aircraft-derived, single-shaft, industrial gas turbine with a nominal 9.5:1 pressure ratio and 1895 DegF turbine inlet temperature (TIT). The Cheng cycle adaptation of the engine is identified as the 501-KH. The 501-K engine was chosen for a number of technical reasons including its compressor's large surge margin, combustion section design, efficiency, fuel flexibility, serviceability, and experienced base of engine packagers. In addition, the single shaft arrangement enhances generator stability, is readily adaptable to mechanical power increases, and allows the additional work from steam to be extracted, without the additional control loops otherwise required for injection balance and speed control of a free turbine version.

**PERFORMANCE MODELING** - Computer programs have been developed which allow engine performance prediction over the full range of ambient conditions, firing temperatures, and steam injection rates. Specific algorithms address the unique areas of mixed-fluid (steam and air) expansion in the turbine, variable compressor pressure ratio as a result of injection back pressure, variable compressor and expander efficiencies as a result of varied cycle mass flows and pressure ratios, and the corrections to combustion calculations required because of the presence of steam with its high specific heat. The regenerative nature of the cycle requires iterative techniques since the engine exhaust characteristics both influence, and are influenced by, the total steam injection rate. Also, the engine's outlet losses and to a lesser extent, the inlet losses, modify and are modified by the injection rate and the duct firing rate.

**COMPRESSOR** - Steam injection adds mass flow through the expander(s) of the gas turbine. This added flow does not get compressed by the engine's compressor; hence, it does not require the work of compression as does the base quantity of Brayton cycle air. For a given TIT, the added expander flow requires a higher pressure ratio in constant-speed service. Overall, steam injection back-pressures the compressor and there is a need to re-match the load line characteristics of the compressor/expander as a function of the injection steam flow.

Re-matching is complicated by the fact that a pound of steam is the equivalent of 1.6 pounds of air (on a volumetric basis) due to the molecular weight ratio of air and steam. Analysis of the compressor characteristics allowed IPT to predict the equilibrium pressure ratio and the subsequent change in compressor work function and surge margin. With the proper choice of operating speed, the surge margin and other compressor characteristics of the base 501-K proved to be acceptable for Cheng cycle operation without requiring changes to the aerodynamic hardware.

Surge margin retention is further enhanced by IPT's development of real-time control algorithms which monitor surge margin and force a reduction in power level when surge margin reserve has been depleted due to adverse ambient conditions or hardware malfunction. Furthermore, these control actions are backed by a dedicated surge/flameout detector which monitors the rate-of-change in compressor discharge pressure and shuts down the engine in the event of a failure of the control hardware.

**OPERATING SPEED** - Traditionally, the 501-K engine is operated at 13,800 RPM for generation service. As with most of the "rules of thumb" developed from prior applications of the 501-K engine, Cheng cycle adaptation benefitted from re-evaluation of the operating speed choice.

After considering shaft torque capabilities, compressor and expander efficiencies, surge margin, airflow changes, stress rupture lifetimes, and rotor characteristics, 14,600 RPM was chosen for Cheng Cycle Series 7-Cogen applications.

**INJECTION GEOMETRY** - Various steam injection arrangements were considered for the 501-KH adaptation. The chosen geometry provides for steam entry and mixing with the compressor discharge air at two locations; one immediately downstream of the compressor diffuser and another farther downstream, adjacent to the combustion liners. These two locations each provide for uniform circumferential distribution via orifices machined directly into the standard outer combustor case. The distribution orifices are fed by a pair of ring manifolds, one for each location. The manifolds are integral with the outer combustor case and share a common wall with the case. The manifolds themselves are each dual-entry, resulting in a total of four external steam ports. Finite element design and specific fabrication expertise was required of Allison to avoid thermal growth distress in this compact assembly, which also serves as the "backbone" of the engine.

Several benefits result from this design approach. All mechanical changes required to accommodate steam injection are confined to this one component, maximizing standardization of the rest of the engine. The engine's envelope dimensions, center of gravity, mounting locations, assembly, and test procedures remain essentially unchanged compared to the standard engine. The low overall pressure drop allows the application of ASME Section I Boiler Code Case 1966 (an IPT-submitted Code inquiry), eliminating problematic safety and block valves downstream of the superheater.

**COMBUSTOR** - Steam injection is arranged to take advantage of the airflow patterns and pressure drop characteristics around the combustion liners to ensure rapid, uniform mixing of steam without perturbing the original airflow distribution. The burner outlet profiles were examined with special instrumentation to confirm similarity with the non-injected profiles, ensuring a hot section lifetime similar to that of the standard engine. Both lean and rich flammability limits were explored to confirm combustion stability with the increased heat release rates (20%) associated with Cheng cycle operation. Strengthened transition sections, improved coolant use, and ceramic coatings are resultant combustor improvements developed by Allison for the 501-KH (and the 501-KB5).

Emissions characteristics of the engine have been another area of technology development associated with the combustor. The presence of steam injection produces significant reductions in $NO_x$ production - from 100-130 $ppm_v$ for the standard engine to 10-20 $ppm_v$ for Cheng cycle (dry basis, corrected to 15% $O_2$). This occurs without the undesirable thermodynamic and operational drawbacks of water injection. Two mechanisms appear to be involved; the larger specific heat of water serves to buffer the peak flame temperature and the large volumetric quantities of inert steam involved suppress the partial pressure of oxygen.

An IPT-developed procedure called "staged steam injection" works in conjunction with the dual injection manifolds, further enhancing $NO_x$ suppression at low and intermediate steam injection rates. An external control valve in the injection piping restricts injection to the downstream manifold during reduced steam injection rates. Hence, steam is preferentially diverted to the upstream manifold where it can have the greatest effect on the primary and secondary combustion zones. (The downstream manifold has greater effect on the dilution zones and outlet temperature profiles.)

**WATER INJECTION** - In some Series 7-Cogen applications, water injection is used in addition to steam injection for coordinated $NO_x$ reduction. This need can occur when little or no injection steam is available due to a large process steam demand and/or due to economic considerations. Water injection is commonly applied to the base engine wherein water flow rates are simply proportional to fuel flow rates. Coordinated water injection for the 501-KH required development of hardware and control strategies which provide for water flow in proportion to fuel flow and inversely proportional to steam flow. For a given TIT, this results in bivariate control since fuel flow is also linked to the steam injection rate.

As steam injection is increased from low values, Cheng cycle water injection is appropriately decreased, attaining zero value at an intermediate injection steam flow rate. IPT's technology also addresses problems associated with low absolute water flow rates, including turndown limitations imposed by control and metering considerations, water boiling due to conductive heating in the fuel nozzles, poor atomization, and improper drainage.

Dual fuel (liquid and gas) applications produce an additional level of complexity since injection water passes through the unused-fuel passageway of the fuel nozzle. In addition, fuel changeover must occur "on the fly" with no power reduction or shutdown required. Fuel nozzle lifetime is enhanced by always maintaining a trickle flow of purge gas through all unused nozzle passageways. This avoids plugging from dried fuel oil or water residues and prevents thermal damage from the recirculation flow induced by the inevitable small combustor-pressure imbalance. Overall there are as many as eleven interdependent fluid flows which must be coordinated depending on operating mode: pilot fuel oil, pilot purge gas, main fuel oil, main purge gas, gas fuel, gas-side injection water, liquid-side injection water, pilot-side drain, main-side drain, upstream injection steam, and downstream injection steam.

Still in progress are technology developments which will allow saturated steam injection through the fuel nozzle directly to the primary combustion zone. On gas-fuel-only applications, this will serve as a desirable substitute for water injection, providing the Series 7-Cogen with a flat-rated emissions characteristic, and eliminating the separate water injection system with its operating drawbacks and maintenance difficulties. Also being developed (by Allison) is a dual fuel nozzle with a dedicated water injection port which will eliminate most of the complexities associated with fluids multiplexing in current dual fuel applications.

**EXPANDER** - The 501-K engine uses internally-cooled hardware for the first stage turbine blades and vanes; compressor discharge air is passed down the length of the combustion case and metered through orifices in the vane support to these coolant passages. The addition of steam to this airflow results in the blades and vanes being cooled by a mixture of air and steam. This required revisions to the heat transfer calculations which predict metal temperatures, and hence lifetimes, of the critically loaded first stage hardware. The calculations are complicated by the presence of steam on *both* sides of the metal surfaces. Steam, having a higher specific heat than air, is a more effective coolant on the inside surfaces. However, steam is also mixed with the combustion products which are heating the outside surfaces, resulting in increased heat transfer into these components. A test engine fitted with special instrumentation, including optical pyrometers and vane temperature thermocouples, was operated under actual field conditions to confirm these predictions.

Ongoing technology development will allow isolating these coolant passages from their normal air flow, and providing 100% saturated-steam cooling for the first stage hardware. This is a double-edged improvement. Compressed air, which is expensive from a thermodynamic view-point, will no longer need to be "stolen" from the cycle for cooling purposes; this results in a direct performance improvement. In addition, the availability in Cheng cycle of saturated steam for use as a coolant allows a substantial reduction in metal temperatures. This reduction yields increased engine lifetime and/or improved cycle performance from the use of higher allowable firing temperatures.

The base 501-KB5 expander features specialized coatings on the exterior surfaces of the first stage blades and vanes to provide protection from the high temperature combustion gases and to suppress corrosion. Until the 501-KH development, the internal surfaces of this hardware were uncoated, being exposed only to cooling air. The addition of steam to the air flowing through these internal surfaces, with the possibility of chemical carryover from upsets in the boiler, required extending the coating processes to include the interior surfaces as well. These surfaces are of complex geometry and specialized fabrication expertise was developed by Allison to integrate the coating processes with the intricate assembly steps involved. These improved components have subsequently been applied to the rest of the 501-K product line, ensuring commonality for the 501-KH.

**POWER INCREASE** - Several areas of the engine required examination and/or modification by the engine manufacturer because of the increased power output of the Cheng cycle adaptation (approximately 4700 to 8700 shp). The power output shaft was modified via increased diameter of its overload shear section. The compressor extension hub was strengthened by designing extended splines which could be machined from the original forging. The engine's internal thrust balance was modified to retain the original thrust bearing lifetime. Improved crossover tube assemblies have been developed to extend combustor lifetime.

The higher pressure ratios associated with Cheng cycle operation triggered several additional minor changes to lighthouse seals, labyrinth seals, cooling air flows, and oil scavenge considerations. In addition, the turbine inlet case was improved by changing from the original welded assembly to a higher-strength, single-piece casting.

A notable feature of all the redesigned components is their compatibility with the rest of the Allison 501-K product line; in fact, following their original development for the 501-KH, all of the changes discussed have since been incorporated into the other 501-K engines.

**MOISTURE CONTROL** - Specific attention has been paid to the control of the added moisture imposed by steam injection on various engine systems. Turbine labyrinth seal materials have been selected for improved immunity to moisture. Additional combustor drain valves have been added by Allison to accommodate the steam manifolds, which became the new low points of the outer combustor case.

Special startup and shutdown procedures are implemented in the Cheng cycle control system to prevent the entry of condensed steam into the engine; as part of the start sequence, compressed air is taken from the engine by *reverse* flow through the injection piping to purge and pre-heat the superheater and the steam injection piping. The same technique is used during the normal shutdown sequence to prevent condensation from collecting and entering the turbine during the next start cycle. During each startup and shutdown, this reversed flow of air also serves to dislodge any material which may have collected on the steam strainers; they are externally located in the steam piping, just before its entry to the genset.

**STEAM PIPING** - The mechanical and thermal design of the injection steam piping between the engine and genset frame required special expertise to deal with a multitude of complex trade-offs. The piping bridges two contrasting design worlds; on one side is industrial power piping design, with its appropriate ASME standards, emphasis on bulk and weight, and generous safety margins. At the engine side, the design is derived from aircraft standards which favor lightweight construction, high strength materials, compact layouts, rigorous quality controls, and smaller safety margins.

This interconnecting piping must handle the complex thermal growths of the engine without undue loading either on the steam manifold flanges or the engine itself. At the same time, the piping must accommodate its own thermal growth at a design operating temperature of 1000 DegF. The articulated joint design chosen by IPT also addresses maintenance access, engine removal, engine interchangeability, and thermal loading of the compartment ventilation system.

**FUEL SYSTEMS** - The increased heat release rate requirements of the Cheng cycle version required modifications of the 501-K fuel gas control valve and its associated electronics. The basic flow capacity of the valve was increased approximately 30% and a revised calibration of the valve electronics restored light-off fuel flow to the original value of the base engine. The fuel control schedule was also revised to alter the dynamics of the start/run transition. The need for these changes is triggered by the increased "virtual" combustor volume associated with the added capacity of the attached steam piping and the increased inertia of the larger gearbox/generator required for Cheng cycle operation. As with most 501-KH engine developments, these fuel system changes have been applied by Allison across the 501-K product line.

**EQUIPMENT SIZING** - Since the 501-K engine had an established record of reliable industrial applications, many component selection and arrangement "habits" were almost automatic. IPT applied its expertise to careful examination of these standard choices with an eye toward retaining proven practices. At the same time it was necessary to confirm or reestablish these choices as being appropriate to the requirements of Cheng Cycle Series 7-Cogen; the majority of initial applications for the product were to be in cogeneration service, with its unique emphasis on performance, reliability, and flexibility in a challenging economic environment.

The "standard" main reduction gearbox, for example, had to be re-sized for higher power levels, and the reduction ratio was altered for greater compatibility with Cheng cycle operation. Radial tilting pad bearings were chosen in lieu of plain journals for the high speed pinion to improve reliability over the wider load range of the 501-KH. Starter pad provisions were examined for compatibility with increased torque input and higher starter dropout speed. The low-speed shaft, shear pins, and low-speed coupling were also re-sized.

The generator required the obvious capacity increase as well as fresh consideration of the process of matching generator and turbine derating curves. Generators in this size range are invariably forced-air cooled, and must be derated as the ambient temperature increases. A simple gas turbine similarly suffers a capacity decrease with ambient temperature increase since engine power output depends on air density. The usual result is a complementary match between the turbine's ability to produce power and the generator's ability to accept power, since both effects are linked to a common ambient temperature. In Cheng cycle applications, the engine's capacity is not limited in exactly the same way, since power output can be significantly boosted by injection steam, even at high ambient temperatures. Finally, the generator's part-load efficiency curve was modified after consideration of the economics of continuous cogeneration service.

Starter sizing required consideration of the increased breakaway torque and the increased starter assist required to compensate for the larger generator, 501-KH extended dropout speed, and the requirement for a boiler/ductwork air purge during the start cycle prior to engine ignition. The start system design also accommodates extended motoring service during compressor wash/rinse maintenance activities. The design evolved into an arrangement consisting of an electric motor which is close-coupled to a variable displacement hydraulic pump. The pump connects via hoses to a variable displacement hydraulic motor which is directly mounted on the gearbox, and connects to the power train through an over-running sprag clutch. The design features cascaded hydraulic controls for the two variable displacement elements, and provides torque limiting at breakaway, over-running protection, and smooth torque/speed crossover over an extended region.

**LUBRICATION SYSTEM** - The genset features a common lubrication system for engine, gearbox, starter, and generator. This simplifies instrumentation, oil filtering, cooling, and level control and avoids any inadvertent mix-up which might occur when different lubricants are used. In addition, the design eliminates any danger of cross contamination at the engine/gearbox interface due to seal failure at the power take-off shaft. Provision is made for the increased heat rejection from the larger components, and for pre-lube and post-lube of the heavily loaded journals at low speeds.

In Cheng cycle operation, steam injection of the 501-KH unavoidably substitutes water vapor for some of the normal labyrinth seal air flow. This air and steam mixture is discharged from the engine as usual, along with the return oil flow. Similarly, the engine's breather also discharges a mixture of air and steam. Special IPT design features control foaming and enhance moisture extraction from the turbine scavenge pump discharge flow and engine breather flow.

The well-proven, ester-based, synthetic lubricants traditionally used for aircraft-derived gas turbines suffer from high cost, toxicity, disposal problems, and limited compatibility with seal materials. Of greater concern, ester-based lubricants are hygroscopic, and deteriorate in the presence of self-absorbed water via hydrolysis. The resulting acidity increase is the major cause of otherwise premature oil change-out.

Steam injection and the resultant increased exposure of the oil to high moisture concentrations accelerates this deterioration of ester-based lubricants. IPT, working with a major lubrication supplier and Allison Gas Turbine, has initiated the development of a lubrication oil specifically tailored to Cheng cycle operation. (The oil is also well suited to use in a standard gas turbine). This synthetic oil is compounded from a non-hygroscopic, polyalphaolefin base stock and retains all the desirable properties of the ester-based oil it replaces. It is of lower cost, non-toxic, and compatible with a wider range of seal materials. Of particular importance to Cheng cycle service, it does not absorb water nor does it deteriorate by hydrolysis.

An initial field test exposed a weakness of the additive package used in the new oil: the additives would wash out of the oil in the presence of water, and deposit sludge in regions of high centrifugal separation force, such as those found in the interior of the engine's rotating components. The additive package has since been revised to eliminate this tendency, and the oil has passed the battery of laboratory evaluation tests required by Allison's Material Specification Group. The oil will undergo final field tests this summer at an IPT-operated Series 7-Cogen plant, completing its qualification as a approved, Allison EMS-45 lubricant.

**GOVERNOR** - To the extent possible, the Allison-supplied, core set of turbine controls has been left intact. They provide a standardized interface with the engine, basic protective functions, and the fundamental fuel control schedules. However, with steam injection, Cheng cycle adds a significant energy input source to the turbine which is not under the direct control of the governor. IPT has developed the control extensions required to accommodate this additional degree of freedom, and has encompassed the governor within a larger shell of distributed digital control. The engine, via its governor, is managed as one of the many subsystems coordinated by the Cheng cycle system controls.

## HRSG/CYCLE TECHNOLOGY

Within this layer, Cheng cycle technology addresses the heat recovery steam generator (HRSG), duct burner, and the remainder of the components required to complete the thermodynamic specification of the cycle. It is at this level that the teachings of the IPT patents are translated into actual hardware, and ideal academic optimization is tempered by engineering and economic realities.

A major consideration throughout all levels of the technology is the large turndown capability of the Cheng Cycle Series 7 equipment. Especially in cogeneration service, it is important to follow, smoothly and efficiently, both thermal and electric loads over the full range from zero to maximum capability. The Cheng cycle approach to cogeneration promises this rangeability without a complicated equipment arrangement; realizing this flexibility is a major goal of the technology in this layer.

**BASIC DESIGN** - After examining several original approaches to a boiler designed specifically for enhanced operation with Cheng cycle, IPT chose to modify and extend the capabilities of "standard" HRSG designs. As with the genset equipment selection process, this required that entrenched "rules of thumb" be scrutinized for appropriateness to Cheng cycle and cogeneration service. Steam conditions required by this application (approximately 950 DegF at 200 psig) are characterized by the temperatures found in utility power boilers; at the same time, pressures are characteristic of commercial process boilers. IPT has retained the suitable features of both boiler types, and has avoided inclusion of inappropriate design requirements from either type. The boiler is required to provide large turndown and accommodate various operating modes, with various combinations of turbine firing rate, duct burner firing rate, and steam injection rate.

Natural circulation was chosen over forced circulation. This choice denied the size and weight benefits provided by a forced circulation design, and required the total HRSG to be shipped in sections. Nevertheless, the benefits of a natural circulation design were considered essential for Series 7-Cogen: one less pump required, tolerance to drum chemistry variations, transient and upset capability, wide turndown, conventional fabrication requirements, and repairability.

The HRSG includes a superheater for injection steam, duct burner, two-drum evaporator, economizer, deaerator, counterflow liquid-to-liquid feedwater heat exchanger, blowdown heat exchanger, flash tank, stack, and automatic blowdown control. IPT specifies all of these components in order to control plant overall energy balance, plant construction uncertainty, and plant reliability. Although common in simple gas turbine applications, a gas diverter valve is not required in Cheng cycle applications since there is never excessive turbine exhaust energy which has to be dumped during reduced process steam loads. Under such conditions, "excess" energy is captured by the HRSG and profitably returned to the cycle in the form of injection steam to the gas turbine.

**PERFORMANCE MODELING** - IPT has developed specialized computer programs which are used for both synthesis and analysis of the HRSG. These same programs link to the turbine performance models to provide analysis of the overall plant performance. Specific attention is paid to handling mixed-fluid properties correctly, and the regenerative properties of the overall cycle are correctly iterated. Performance prediction also includes consideration of the deaerator requirements, flash steam production, blowdown losses, and duct burner augmenting air balance, since these elements influence the total heat balance and are part of the standardized scope of supply.

Modeling has also been used to clarify the availability of energy from the stack gases at temperatures less than the lower pinchpoint temperature. Under virtually all operating conditions, low-grade energy requirements are supplied entirely by the stack gases; although Cheng cycle can require large quantities of makeup water to be heated, these are the very times when additional energy is available from the stack. Hence, there is no thermodynamic need for any complex, plant-wide, waste-energy recovery systems from sources such as the generator, lube oil cooler, and gas compressor. All these components are individually air cooled, allowing maximum flexibility in their placement and operation, and avoiding interaction among any of these systems and the rest of the cycle.

**SIZING** - The process of sizing the heat recovery components is complicated by the various operating modes provided by Cheng cycle cogeneration. Base sizing is derived from requirements of pure power operation (no duct burner or process steam): the cycle pressure ratio defines the drum saturation temperature after allowance for the pressure drop requirements of the injection steam piping, superheater, and injection control valve.

An estimated injection rate, along with the engine characteristics, then determines the turbine exhaust temperature and composition. The economic cost/recovery characteristics of additional surface area increments define the appropriate boiler pinchpoints (approach temperatures). The superheater can now be sized, and the gas-side conditions at the entrance to the evaporator are then determined. The evaporator is sized next, and a new steaming rate is determined. This rate is checked against the estimated steaming rate, and the calculations iterated as required.

Given the deaerator pressure and make-up temperature, all gas-side and liquid-side conditions are now defined, permitting the rest of the cold-end components to be chosen. Note that the 501-KH engine will accommodate and make optimal thermodynamic use of all the waste-heat steam provided by this basic Cheng-cycle sizing. This important characteristic permits peak generation efficiency at any power level, even when there is zero demand for process steam.

Alterations are made to this basic sizing to accommodate the extended capabilities provided by the duct burner, site specific requirements for process steam pressure, site condensate return conditions, deaerator consumption, blowdown rate, and to balance cold end heat recovery. The final standardized design accommodates these wide-ranging requirements, with essentially no required hardware changes from site to site.

**COLD END DESIGN** - Those portions of the HRSG located in the gas path downstream of the evaporator, referred to as the cold end, are responsible for recovering sensible heat from the stack gases in order to maximize the recovery of latent heat (steam production) in the evaporator. However, the design criteria for these sections are contradictory at different operating modes. A design "undersized" correctly for the lowest steaming rate will fail to capture otherwise useful energy at higher steaming rates. If the design is properly "oversized" for the highest steaming rate, it will recover an excess amount of energy at lower steaming rates, resulting in deaerator upsets, premature boiling, hammering, and erratic feedwater heater/economizer performance. The conflict occurs because the gas-side flow and temperature at the lower pinchpoint remain essentially unchanged in spite of changes in steaming rate or operating mode; they are fixed by the drum saturation temperature at the operating pressure and by the flow characteristics of the gas turbine.

IPT has designed a simplified approach to cold end heat recovery which sidesteps this conflict and ensures optimal heat recovery under all operating modes. The conventional feedwater heater is eliminated. In its place is a regenerative liquid-to-liquid heat exchanger which supplies the deaerator's requirements. The regenerative characteristic of this heat exchanger ensures that it is never "undersized" or "oversized". Extra surface area is added to the economizer to compensate for the eliminated feedwater heater, and the economizer pressure is controlled to a level higher than the drum pressure such that no significant boiling occurs in the cold end.

**MATERIALS** - The service duty of the superheater is more like that of a reheater in a conventional utility power boiler. Thermal cycling, high temperature service, and periodic exposure to oxygen all contribute to exfoliation corrosion and are unavoidable characteristics of Cheng cycle (and reheater) service. Small amounts of exfoliated material from the internal surfaces of these components will, in time, plug internal clearances in the turbine and can shorten the lifetime of protective coatings. Thus, materials selection for the steam injection piping and superheater play an important role in maintaining steam purity and avoiding turbine erosion damage.

IPT gained first hand experience with this phenomenon since the first plants were built with the chrome alloy materials normally selected for conventional superheater service. Although no evident damage occurred, fine rust powder accumulated at some stagnant locations within the engine. The superheater was identified as the source of the objectionable powder, and the problem was eliminated at the early plants by developing specialty equipment for in-situ electroless nickel plating of the steam-wetted surfaces. Later units have been constructed using more appropriate materials, and all engines have since been free of rust.

Finned-tube construction is used throughout, with proper consideration of carbon fouling and sootblower access in oil fired service. The high water vapor content, enhanced heat flux, and high duct burner heat release rates under Series 7-Cogen operation also influence fin material selection and spacing. For some applications, when the turbine must be kept online in the event of boiler failure, IPT optionally offers the HRSG designed for limited, "dry" operation.

**TRANSITION DUCT** - IPT has applied its expertise in flow diffusers to the design of the transition section between the turbine tailcone and inlet face of the superheater. The design includes proper consideration of the increased flow rate and altered fluid properties under Cheng cycle operation. The benefits include a shortened footprint, uniform flow distribution to minimize the upper HRSG pinchpoint, and high pressure recovery to minimize backpressure losses in the turbine.

**DUCT BURNER** - A duct burner, or secondary combustor, is included in the Cheng Cycle Series 7-Cogen design to enhance steam production either for increased power production or for increased process steam production. Just as in a simple cycle plant, the addition of the burner is attractive because of its low incremental capacity cost, and its efficient use of fuel due to no additional draft or stack losses.

The traditional location for the burner is just downstream of the turbine in the ductwork leading to the HRSG. In contrast, IPT located the burner for the Cheng Cycle Series 7-Cogen between the superheater and evaporator for three cycle-related reasons:

> A traditional placement would have added additional energy to the injection steam (as well as to the rest of the boiler). This is not desirable since injection steam temperatures greater than turbine exhaust temperature do not benefit the cycle. The turbine's combustor serves as a 100% efficient (direct-contact) heat exchanger, raising injection

steam temperature from turbine exhaust temperature to turbine inlet temperature. Thus, firing in the traditional location would simply have traded, at a net loss, increased fuel consumption in the duct burner for decreased fuel consumption in the turbine.

Injection steam temperatures much higher than turbine exhaust temperature would have unnecessarily complicated the design and materials selection of the superheater and injection steam piping. Higher steam temperatures would also have aggravated thermal stress gradients in the outer combustor case and steam manifolds, as well as compromised cooling air effectiveness inside the engine.

Uniform heat release across the entire gas stream cross-section is one of the primary design requirements of the duct burner. This is difficult if the duct burner is located downstream of the turbine because of the poor flow distribution inherent in the turbine's exhaust. A flow straightening device is often used in a standard plant to condition the gas stream; it provides the uniform flow at the inlet face of the burner which is necessary to achieve uniform heat release. By locating the burner downstream of the superheater, IPT takes advantage of the inherent flow conditioning capability of the superheater itself. This obviates the requirement for a flow conditioning device and its consequent additional pressure drop.

Combustion in the duct burner depends on the residual oxygen contained in the turbine's exhaust gases. Under Cheng cycle operation, injection steam reduces the partial pressure of oxygen and increases the specific heat of the gas stream. The burner is specifically modified to account for these effects which would otherwise cause increased carbon monoxide (CO) production and combustion efficiency losses. In addition, the design incorporates an augmenting-air fan, and an air schedule tailored to both the duct burner heat release rate and the injection steam rate. The result is minimized augmenting-air stack losses coincident with low CO production.

The duct burner's maximum firing rate is limited by a design maximum allowable gas temperature. The burner's heat release rate limits are chosen to take advantage of the increased heat capacity of the exhaust gases when steam injecting, and provide for the increased capacity available under these conditions.

Other technical features of the duct burner include a modified purge cycle (improved response time), and emissions control which is interactive with the engine. Steam and/or water injection applied to the turbine also serves to suppress $NO_x$ formation in the duct burner. Furthermore, CO produced in the gas turbine does not algebraically add to that produced by the duct burner; rather it is substantially eliminated via dissociation and re-oxidation in the burner's flame zone.

**STEAM PURITY** - Injection steam, like other fluids entering the engine, must be clean. In addition, the process of maintaining steam purity must be robust so that the inevitable upsets do not allow unacceptable impurities into the engine <u>or</u> into the superheater. IPT has evolved a multilevel approach to steam purity control which emphasizes simplicity and reliability.

The first step is control of drum chemistry. The process of boiling water is itself the basic purifying step; as steam is produced, impurities are left behind in the drum. Thus the turbine is relatively immune to incoming water quality, and the primary purpose of drum chemistry control is protection of the boiler.

As a side note, filming and/or neutralizing volatile amines are often injected into the feedwater of a process boiler. They are vaporized in the drum and carried with the process steam to provide corrosion protection throughout the steam distribution and condensate return piping systems. With the Series 7-Cogen, it is preferable to bypass the drum and to inject such amines directly into the process steam header; this practice avoids their unnecessary loss through the injection steam line to the stack.

The standard ABMA recommendations for drum concentrations are used in Cheng cycle operation. Compared to most power boilers, these are mild restraints due to the low pressure nature of the Cheng cycle boiler. Nevertheless, because steam purity is slightly affected by the level of drum impurities, IPT uses the ABMA recommendations for one pressure class higher than that which would otherwise be required. It is of interest to note that volatile silica carryover, normally of concern in power boilers and steam turbines, is not significant in Cheng cycle boilers.

The steam drum is of generous size to provide transient capability and low superficial steam velocities at the water surface - both of which contribute to improved steam purity. Two-stage steam separators are used in the drum. Main steam line connections are arranged so that both process and injection steam pass through these separators. This maintains higher velocities and good separation efficiency regardless of the eventual split between injection and process steam.

An additional, external, two-stage steam separator is dedicated to injection steam, further improving its purity. Finally, a set of steam strainers, located downstream of the superheater, provide "last ditch" protection for the engine. Of greater practical importance, the ongoing <u>lack</u> of any significant pressure drop across these strainers provides ongoing assurance that the injection steam purity systems have not deteriorated. Special turbine start/stop sequences, injection steam piping layout, steam traps, and automatically controlled superheater drain valves control any steam condensation, and guard against its inadvertent intrusion into the engine.

**INJECTION CONTROL** - Injection steam control is provided by a quick-closing block valve and a modulating control valve. Depending on operating mode, the control valve automatically adjusts injection flow to satisfy one of several constraints. These include drum pressure, power production, combustion stability, $NO_x$ production, and isolated-grid operation. These valves are also used to suppress boiler level "swell" during startup by temporarily pressurizing the drum with engine air. Also, if required during normal operating conditions, they are used to prevent air from contaminating the process steam system.

The traditional power plant location for such block and control valves is downstream of the superheater. In Cheng cycle, the valves are located upstream of the superheater to improve energy recovery, avoid material problems, and ease condensation control.

**PROCESS CONTROL** - The process flow control valve is included in the design and control scope of the Series 7-Cogen. Although it is of conventional design, it affects overall Cheng cycle operation. Rate-of-change limits are placed on the valve to control drum upsets and steam purity. The flow data are used as part of anticipatory drum level control. The valve is also used to help prevent undesirable reverse flow from the engine to the boiler, and provides for process load sharing, either with a conventional boiler or another Series 7-Cogen unit.

## PLANT/ENVIRONMENT TECHNOLOGY

Technology development in this layer results from IPT's direct participation in the end use of the Series 7-Cogen product. The experience gained in installing, managing, and operating plants has led to improvements and extensions to the basic technology which specifically address the unique cogeneration environment. The major driving force has been the recognition that cogeneration is a specialized "business" unlike that of a traditional power plant or boiler plant. Cogeneration often must be financially self-supporting, and special emphasis is placed on availability and repairability. Cogeneration is often viewed as a source of profit rather than an overhead expense. IPT-developed technology and know-how helps this business be responsive to a complex regulatory, contractual, and permitting environment.

**PERMITTING** - In-depth involvement with all aspects of the Series 7-Cogen product enables IPT to "build in" features aimed specifically at streamlining plant permitting. Examples include acoustical enclosures, equipment guards, fire protection systems, ladders and platforms, piping and piping supports, wiring practices, exposed surface insulation, and venting provisions - all aimed at ready compliance with a broad range of national, state, and local standards and codes.

Nevertheless, air quality issues are usually a most troublesome aspect of permitting a gas turbine plant; hence IPT has developed specific technology and permitting expertise in this area. Cheng cycle's intrinsic use of massive amounts of steam injection results in very low $NO_x$ emissions - lower than any commercially available, proven, gas turbine plant without the use of external add-on catalytic converters.

In addition, Cheng cycle produces a $NO_x$ characteristic significantly *different* from that of a standard gas turbine. $NO_x$ production increases with increased power level in an ordinary gas turbine - it <u>decreases</u> with increased power level in Cheng cycle. Pollutant production measured on a kilowatt-specific or BTU-specific basis is unusually low because of Cheng cycle's high efficiency. The result is that Cheng cycle stands apart from gas turbines, and it often does not readily fit into the standard categories considered by air quality permitting agencies.

The use of various combinations of steam injection, staged-steam injection, direct saturated steam injection, minimum steam injection, and/or coordinated water injection enables IPT to tailor the $NO_x$ characteristics for each application. This achieves the best trade-off between a particular permitting agency's requirements, the site-specific load profile, and any adverse economic impact of emissions control. IPT has established the combined use of staged-steam and water injection as Best Available Control Technology (BACT) for Cheng cycle in California's South Coast Air Quality Management District, one of the toughest air quality regions in the country.

Permitting often stands in the critical path of a cogeneration project's development. Because of IPT's unified approach to the Series 7-Cogen product, permitting assistance, well-established data, and application procedures are all available early in a project, often obviating this timing problem and reducing project development uncertaintities.

**CCEM** - Many air quality districts currently require the installation of continuous emissions monitoring (CEM) equipment. Because of the operational problems associated with these systems, IPT has taken advantage of the equipment uniformity at Series 7-Cogen sites and developed a computational model of pollutant production. This Calculated Continuous

Emissions Monitor (CCEM) is implemented within the Cheng cycle control system, and has been accepted as an equivalent method for monitoring and reporting continuous emissions by several California air quality districts.

**BLACK START** - With a liquid fuel, emergency-power genset, black starting capability is generally provided by including battery capability for the minimal set of controls and the use of a compressed-air or direct-coupled diesel starter. Extending this approach to the Series 7-Cogen product is inappropriate.

Many applications are gas fuel only, and require a that a fuel gas compressor be online to start the turbine. The starter system must supply extended engine motoring for boiler purge during the start sequence and for turbine compressor maintenance. The instrument air compressor, water treatment system, Bailey control system, pre-lube pump, genset ventilation fans, and various HRSG systems are normally active during plant startup. A traditional approach to black start would require a complicated series of interlock overrides, manual interaction, and special procedures to avoid HRSG damage.

IPT provides black start capability by installing a stand-alone diesel generator which is attached to the plant's 480 volt auxiliary bus. This results in "black" starts that are identical to normal starts, the full control system and other plant systems being active, no safety features having to be temporarily overridden, normal use of the automatic synchronizer, and a black start plant configuration that is identical to that of the standard plant.

**ON-LINE EMPHASIS** - Specific design attention is paid to hardware and software features which extend the plant's ability to stay safely on-line in spite of partial equipment failure and throughout maintenance activities. Examples include redundant pumps, provision for redundant control modules, duplex filters, bypass piping around appropriate control valves, auto-manual stations, self-cleaning air filters, and control strategies which cascade to fallback modes. For example, in the event of failure of the water injection system, the operator may specify a "minimum allowable injection steam" setpoint. This places a floor on the injection steam flow rates which could otherwise be reduced due to high process steam demand. The result is that steam injection substitutes temporarily for water injection until repairs are completed, and a potential air quality violation is averted.

**WATER TREATMENT** - Steam injected into the turbine is lost from the cycle as water vapor discharged through the boiler stack. Make up water is also required to replace process steam losses. The proper choice of water treatment methods depends on the quantity and quality of water to be treated, the decision to treat externally versus internally (via boiler blowdown), and the overall plant economics. Hence, IPT views the water treatment system as an integral part of the plant.

Although water treatment requirements can be very site-specific, the Series 7-Cogen provides for a generic water treatment system based on zeolite softeners and polyamide membrane reverse osmosis. This results in automatic integration of the water treatment system into the plant controls, proper consideration of the overall costs for water, robust designs from previous experience, coordinated chemical injection programs, and the basis of integration for all the various plant water requirements (boiler and condensate makeup, steam and water injection supply, filter and media reverse-wash, and engine compressor wash).

**UTILITY INTERCONNECT** - Generation in parallel with the connected electric utility involves the addition of active sources to the utility's otherwise "passive" electric power distribution system. In fact the entire design basis of such systems is often thwarted since safety provisions, protective relaying, power flow, and feeder reclosure often depend on the assumption that there are no active generation sources on the distribution system. IPT has developed expertise in the design of utility interconnects which addresses these problems.

The design of the Series 7-Cogen's electrical equipment is aimed at accommodating other site-specific interconnect issues including complex utility and third party metering arrangements, site emergency requirements, reactive power support, synchronization protection, utility remote-blocking requirements, power import/export restrictions, and isolated-grid operation with automatic return to the utility.

As with permitting issues, IPT offers utility interconnect design and utility contract negotiation assistance, fitted to the Series 7-Cogen design, early in a project's development. The timing of these services is especially attractive from a project development viewpoint since interconnect costs are highly site-specific. As such, these costs are not easily predictable, and historically they have been an erratic yet significant percentage of a project's construction costs.

**PERFORMANCE TRACKING** - The same modeling capability developed by IPT for plant design has been modified to provide real-time performance monitoring for an owner/operator of the Series 7-Cogen plant. The performance model runs within the overall control system, and continuously displays discrepancies between actual values and expected values for key parameters such as power, fuel flow, compressor discharge pressure, process steam flow, and turbine exhaust temperature.

Careful selection of dependant versus independent parameters quickly isolates specific plant problems to which the operator can respond. This is an invaluable tool for spotting equipment malfunctions, planning operating strategies, and scheduling maintenance. Because of the integrated controls, these trends are easily inserted into the normal alarm, logging and archiving activities provided for the remainder of the plant.

**OPERATING STRATEGIES** - One of the most attractive features of Cheng Cycle Series 7-Cogen is the ability to vary independently electrical production over a wide operating range while simultaneously tracking process steam requirements. This flexibility is achieved, without complex hardware systems, by control of steam injection rate, duct firing rate, and turbine firing temperature. Such electrical production freedom provides the ability to respond favorably to economic variations in utility electric rate schedules, site electrical consumption, capacity payments, demand charges, and fuel prices. IPT has developed three extensions to the Cheng cycle control system which enhance the usefulness of this capability:

- After economic commodity parameters are input by the operator, the control system displays a real-time value for gross profit in terms of $/hour. This value is computed based on concurrent plant consumption and production.

- Another tool provides a suggested set of economically optimal operating strategies derived by "running" a model of the plant using period and cost data entered interactively by the operator.

- The third tool accepts a chosen operating strategy and automatically shifts the plant operating mode accordingly, based on actual time-of-day and rate periods specified by the operator.

## INSTRUMENTATION AND CONTROLS

Controls represent a unique area of IPT's technology development. Throughout each layer discussed above, the controls embody, extend, and unify Cheng cycle expertise. Since the foundation of successful controls is instrumentation, IPT also places special emphasis on the correct selection, installation, and use of instruments in the Series 7-Cogen product.

**INSTRUMENTATION** - In addition to basic support of the control system, instrumentation selection is tailored to several other requirements of the Series 7-Cogen product. Operating flexibility and turndown are key features of the product; this demands instrumentation systems throughout the plant which provide more than the usual two to three times turndown capability. Reliable performance tracking depends on quality measurements of small differences over time; this implies high accuracy and low drift characteristics. Regulatory compliance, maintenance costs, commodity billing, contractual obligations, and the intrinsic profit-oriented nature of the cogeneration business are other examples of demanding instrumentation requirements. IPT has developed an experience base for the selection of instrumentation systems designed to satisfy these requirements.

The injection steam flow metering system serves as a illustrative example of a demanding instrumentation system. The systems and/or functions which depend on this measurement include:

- Start-up logic to purge air from the steam drum
- Plant performance indices
- Compressor performance program
- Surge avoidance controls
- Injection water schedule
- Calculated Continuous Emissions Monitor model
- Flameout controls
- Drum level controls
- Dual fuel crossover controls
- Steam strainer pressure drop monitoring
- Maximum power operating point
- Maximum duct firing limit
- Augmenting air schedule
- Backup $NO_x$ control system
- Staged injection steam controls
- Steam purity maintenance

**CONTROL SYSTEM** - The Series 7-Cogen product incorporates a distributed microprocessor-based control system. This design allows a high degree of automatic plant operation and provides sophisticated operator displays. The distributed architecture places control hardware close to the sensors and final control elements, while providing all essential plant data to the operator. There is a minimum amount of field wiring, thus reducing installation costs and startup problems.

The control logic for the system has been developed by IPT and successfully proven on several operating plants. IPT provides complete support for the system during initial plant start-up and subsequent operation. The control system is fully tested prior to delivery to the site thereby minimizing overall plant installation time.

Standard features of the IPT control system include:

- Color CRT console for operator control and monitoring
- Printer for hard copy of plant data
- Automatic logic for plant start-up and shut down sequencing
- Automatic logic to protect vital plant components
- Local turbine control and indicating stations
- Redundant power supplies
- Trending of important plant parameters
- Live plant graphic screens for both monitoring and control

Optional features are available to further enhance performance:

- Redundant control processors and plant communication systems which increase reliability
- Report generator and data storage system for additional documentation
- Computer interface unit which allows off-site monitoring through a separate computer
- Basic language processor which runs IPT performance and economic analysis programs
- Extensions to the system which integrate control of auxiliary boilers or other plant equipment
- Commodities metering system to provide billing data for electric and thermal production
- Redundant operator terminal(s)

**CONTROL SYSTEM COMPONENTS** - The Cheng cycle control system is primarily based on a Bailey Controls Company *Network 90*$^{tm}$ distributed control system. The control logic and operator displays were developed specifically for the Series 7-Cogen plant. Other control system components have been integrated into the system so that most plant functions can be operated through the console(s). The main control system modules pass data among themselves over a communication system called a "plant loop". The major modules of the system are:

OPERATOR INTERFACE UNIT (OIU) - consists of a color video display and keyboard mounted in a console along with its processor. A separate printer provides hardcopy of graphics screens, data and reports. The OIU provides the means to monitor and control plant operation through indicators, graphic displays, trends and alarms. It also allows manual control of plant processes if required. The OIU communicates with other system modules via the plant loop.

TURBINE CONTROL CABINET (TCC) - located in the control enclosure on the turbine/generator skid. It contains power supplies, input/output terminations and the Process Control Unit (PCU) responsible for the control functions of the turbine/generator and its associated systems. The PCU is also connected to the plant loop.

SKID CONTROL MODULE (SCM) - also located in the control enclosure on the turbine/generator skid. This panel contains the turbine governor system, automatic synchronizer, manual control stations, indicators and other components related to control of the turbine/generator. The manual stations in the SCM allow control of many of the skid mounted components as though operating them from the OIU. The SCM contains termination units which, along with the indicators and digital logic stations, are tied into the plant loop through the TCC.

GENERATOR CONTROL MODULE (GCM) - located next to the generator circuit breaker. It contains protective relays, generator voltage regulator, switches and indicators associated with the generator and electrical interconnect. The switches and indicators allow an operator to control the circuit breaker and perform manual synchronization of the generator if required. The GCM contains termination units which are connected to the control system components located in the TCC.

HRSG CONTROL MODULE (SGCM) - includes power supplies, input/output termination units and a PCU responsible for control functions associated with the HRSG, duct burner systems, and balance of plant equipment. The SGCM is connected to other control system modules via the plant loop. This cabinet may also contain an optional Computer Interface Unit (CIU) used for remote plant monitoring over dial-up or dedicated telephone lines.

BURNER FLAME SAFEGUARDS PANEL - mounted on the duct burner skid adjacent to the HRSG, this panel contains the basic logic for duct burner flame ignition and monitoring. Although manual control switches and status lights are located on this panel, all burner operation is normally accomplished through the plant control system at the OIU.

**CONTROL SYSTEM FUNCTIONS** - The control system operates on several levels to provide integrated plant-wide control. These operating levels are summarized below:

START/STOP SEQUENCING - contains the necessary sequential logic and interlocks required to start the plant automatically from either a cold or hot condition. The only manual action required for a successful start involves boiler valve lineup, and duct burner logic reset after the turbine is running. Automatic plant shutdown sequencing is also provided. These sequences include specific features developed by IPT for the requirements of Cheng cycle.

OPERATIONAL CONTROL - the system continuously controls plant devices in order to maintain stable conditions. Important control loops include drum level and pressure, turbine and duct fuel, injection steam and water, process steam header pressure, make-up water, augmenting air, and emissions. These control loops ensure that the plant is operated in a safe, efficient manner within the limits of desired turbine firing temperature and power output. Process steam demand is given priority to ensure an adequate supply to the process.

PROTECTIVE MONITORING - the control system continuously monitors important plant operating parameters and provides alarms and automatic action which enhance personnel and equipment safety. Particularly important are steam drum level and pressure, turbine temperature and speed, rotating equipment vibration and temperature, oil pressure and temperature, duct burner flame safety, and turbine skid fire protection.

DATA LOGGING - the OIU enables the plant operator to monitor important parameters by means of clearly presented screen displays. Most parameters are graphically trended, enabling immediate, comparative review of the data from the previous twenty-six hours of operation. Alarms are summarized on one screen and can be printed automatically at time of occurrence. Optional features of the system generate reports which average and totalize selected parameters on a periodic basis. An additional option is available for long term storage of data on floppy disks which aids maintenance of plant records.

ECONOMIC OPTIMIZATION - the control system will automatically operate the plant in the mode that has been determined to be optimal, based on economic factors. The logic accounts for electric rates which vary on a daily, weekly and seasonal basis, and changes the plant mode in response to these factors. Operating modes available for implementing an economic operating strategy include:

*Floating Power Output* - electricity produced varies with the amount of "excess" steam available for injection after process demands are satisfied. Extra duct fuel is not consumed to augment power generation, but may be consumed to satisfy process demand after injection steam has first been reduced to its lowest allowable level.

*Power Output Matching Site Demand* - generated power matches the site use so that there is neither import nor export of power at the utility inter-tie. Extra duct fuel will be burned only as required to meet this condition and concurrently satisfy process demand.

*Maximum Power Output* - maximum electrical output is produced in order to minimize site import at times of high retail rates or to export electricity to the utility at times of favorable buy-back rates. Enough duct fuel is burned, both to satisfy process demand and to maintain the maximum allowable injection steam rate.

## INTEGRATION AND PACKAGING

IPT's unified design approach to the Cheng Cycle Series 7-Cogen has produced technological features which result from the synergistic combination of various aspects of the product. Experience has proven that a successful cogeneration project must have its major equipment, as well as all subsystems and components, designed and built as an integrated system.

Integrated protective systems for fire, vibration, electrical fault, and other plant alarms enhance safety and improve availability. Compressed air for plant control can be taken directly from the engine's compressor, eliminating the maintenance and losses associated with continuously running a less efficient conventional compressor. An uncoordinated approach to drain lines and steam traps traditionally results in undesirable interaction and disposal problems. These types of problems are eliminated by design in the Cheng Cycle Series 7-Cogen. Other benefits of integration are:

**SCOPE OF SUPPLY** - An immediate benefit of integration is IPT's ability to provide a scope of supply tailored to the needs of a particular project. Consistent interface definition and design provisions throughout the product allow IPT to supply the equipment modules alone for assembly by others, a complete power island ready for interconnection by others, or a fully installed, turnkey plant. An additional range of services offered derives from IPT's integrated technical approach; they include complete permitting, operator training, project financial forecasting, utility contract negotiation, and plant management.

**EQUIPMENT MODULARITY** - Because IPT has design control over the entire system, it has been possible to group components into pre-engineered modules which simplify installation of the entire plant and dramatically reduce engineering and design costs. Benefits include improved quality due to shop fabrication and testing, reduced field fabrication, reduced project management costs, and streamlined plant commissioning. Maintenance is enhanced because layout and design are planned in advance; the feedback from actual operating experience is embedded in the modules.

**TRAINING** - IPT has developed specific operator training lessons and materials for the Series 7-Cogen which are derived from total familiarity with the product. These standard courses take two weeks, are given on-site, and provide owners and operators with component, system, and procedures training. Uniformity of specifications, drawings, and design philosophy greatly enhance the programs. This is in contrast to the usual approach which might simply gather specifications sheets and generic equipment bulletins into an uncoordinated presentation.

**CONTROLS** - One of the best examples of beneficial integration comes from IPT's total system controls responsibility. Controls are simultaneously the method and the result of IPT's unified approach. When possible, consistent instrument types, interface levels, suppliers, calibration methods, wiring diagrams, tag names, and engineering units apply throughout the product and throughout the finished plant. The benefits include reduced maintenance costs, rapid familiarization, spares flexibility, and improved availability.

## OPERATIONS AND MAINTENANCE

Operations and Maintenance provisions are included by design throughout the Cheng Cycle Series 7-Cogen product. IPT is in a unique position to incorporate maintenance features because IPT also owns and operates some of the same plants it designs and installs. Operation and maintenance are treated as the logical end result of the entire process, not as an afterthought.

The technology is based on providing the features and flexibility of a complex power plant without the mechanical complexity and multiple equipment trains normally associated with such a plant. The apparent "complexity" of Cheng cycle derives from the *arrangement and use* of a minimal set of hardware, not from a complex design. This uncomplicated configuration is the foundation of enhanced operations and maintenance; "if it's not included, you don't have to fix it".

**HARDWARE PROVISIONS** - Careful selection of proven components and design integration ease maintenance throughout the plant. Many of the benefits of established aircraft engine maintenance practices apply to the Allison 501-KH engine chosen for the Series 7-Cogen; although it is an industrial gas turbine, it is derived from a popular aircraft design. This provides and ensures parts availability, shop and/or field repair, ongoing improvements, rapid repair turn-around, and the availability of modular, exchange engine sections. IPT (and others) makes spare engines available so that downtime due to serious engine problems can be limited to the half day it takes to change the entire engine.

IPT further enhances maintainability of the engine with specific design features including a built-in crane, chainfall, and lifting bar for engine removal, space provisions for hot section removal without disturbing engine alignment, centralized interface for engine fluid connections, and an engine mount tailored to maintenance inspections. The injection steam piping includes supports to ease handling and prevent inadvertent bellows damage, special flange designs for wrench clearance, and joints located so as to minimize the piping disturbed during engine removal.

Similar thought goes into the remainder of the plant design. Non-contact, non-wearing labyrinth seals are used on all the primary power train shafts. Self-cleaning turbine inlet air filters lengthen the replacement interval and improve performance. A headset intercom system is integrated into the design, allowing verbal communication throughout the plant. Service air, water, and electrical power are distributed across all modules. Quick disconnect fittings, windows and viewports, and specific control provisions aid engine compressor maintenance. Pre-assembled modules and standardized layouts promote easy maintenance access; the placement of valves, strainers, calibration points, ladders, and platforms is based on proven experience.

**"SOFTWARE" PROVISIONS** - Specific controls development is aimed at easing operations and maintenance. Auto/manual provisions are included for most devices to aid in troubleshooting, calibration, and emergency operation. In addition, remote displays and control stations acknowledge the reality of special operating circumstances. Tested formats for logging, archiving, alarms, and data reports are available from startup, and are easily modified. The majority of critical procedures and practices are well established including startup, operation, shutdown, emergency, routine inspection, annual outage, and instrument calibration.

The system controls incorporate a high degree of automation, such that semi-unattended operation is possible; the result is time available for actual maintenance rather than plant controls manipulation. This is especially true since the Bailey controls are often extended to include existing boilers and other balance of plant systems into an integrated set of equipment.

Based on ongoing experience, IPT has developed an overhaul and repair specification for the 501-KH engine. The use of this specification ensures engine repairs which incorporate appropriate upgrades, avoid unnecessary expense, and draw upon the experience of the entire fleet of 501-K engines. This specification also includes reference to optional extensions of the basic Allison requirements which have been proven desirable in a cogeneration environment. A specific example is the use of special coatings in the compressor which enhance compressor cleanliness and lifetime.

**THERMOCOUPLE MONITOR** - The Allison 501-KH engine uses thermocouple assemblies located directly in the combustor outlets to monitor and control turbine firing temperature. Proper maintenance of these thermocouples is critical to engine health and plant performance. IPT has developed special graphic displays which present a real-time view of engine firing temperatures and thermocouple condition. The benefit is advance maintenance planning, clear operator understanding, and redundant temperature control protection for this important subsystem.

**CONTROLS** - Although the Series 7-Cogen control algorithms are specially developed, the control hardware is standardized (Bailey *Network 90*$^{tm}$), and was chosen deliberately for serviceability. An operator thus enjoys all the service and support benefits associated with a worldwide controls supplier. Service is accomplished on a modular basis; critical cards can be redundantly installed and such card replacement accomplished on-line. Modules are self-diagnostic and the integrated system software displays system status and/or faults in a manner consistent with the other plant status displays. Input/output modules are self-calibrating to a large degree, and the Bailey system software contains provisions which streamline calibration.

**SPARES** - IPT's design uniformity and operating experience reduces required spare parts stocking requirements and increases parts availability. Whenever possible, the same manufacturer, style, or part number is used throughout the plant. Suggested spare parts inventories are established based on prior experience with identical systems. Deliberate design effort has resulted in the 501-KH engine using the same parts as the entire 501-K family. Because of IPT's involvement in plant ownership and operation, shared spares can be made available for expensive and/or critical parts.

Overall, operations and maintenance support has been embedded in the Cheng Cycle Series 7-Cogen product from the first design concepts. Successful "operation" in a cogeneration environment has always been the key driving force behind the technology development process. Quality designs, components, and fabrication can provide long mean-time-between-failures. Equally important, deliberate inclusion of operations and maintenance features provides short mean-time-to-repair.