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THE CHRONOLOGICAL DEVELOPMENT OF THE CHENG CYCLE STEAM INJECTED GAS TURBINE DURING THE PAST 25 YEARS

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ABSTRACT

The Cheng Cycle gas turbine has enjoyed its 25th anniversary since its conception. More than 100 sites around the world including the United States, Japan, Australia, Italy, Germany, and the Netherlands have used the Cheng Cycle. A chronology will be presented in this paper which will highlight the steps taken to develop the fully automated, load following power and cogeneration system. The Cheng cycle operates with a steam to air ratio trajectory that has its highest "peak efficiency" at the onset of a turbine's operation. The peak efficiency point was coined as the Cheng point by Dr. Urbach [ref.1] of the US Navy's David Taylor Research Center. Many thermodynamic and professional textbooks refer to the original Dual Fluid Cycle as the Cheng Cycle. Besides the high efficiency feature, the Cheng Cycle is mechanically simple and flexible in operation. It can put power on line faster than a combined cycle, and it has extremely clean emissions at low cost. The future performance of the Advanced Cheng Cycle will also be projected.

INTRODUCTION

The Dual Fluid Cycle refers to the parallel combination of a Rankine cycle with a Brayton cycle. In the early 1970's, the thermodynamic heat recovery cycle was the way to improve cycle efficiency. A gas-to-gas heat recovery limited the potential for maximum heat recovery, and the industry began to use the liquid bottoming cycle for better heat recovery, now known as the Combined Cycle. The concept of the Combined Cycle started from the mercury topping cycle, and the condenser of the mercury turbine became the steam generator of the steam bottoming cycle. Due to the toxic nature of mercury vapor, the system was abandoned. From a thermodynamic point of view, nothing can be more efficient than the Carnot Cycle, but the Carnot Cycle efficiency is independent of the entropy scale of the cycle. By running a Rankine Cycle in parallel with the Brayton Cycle and raising the operating temperature to the same level as the Brayton Cycle, the thermodynamic potential of the Rankine working fluid can be increased by many fold. This provided the clue that a Dual Fluid Cycle had the potential to be more efficient than a Combined Cycle. In order to achieve high efficiency, the question was how to fill the equivalent Carnot Cycle box as full as possible. Because the Rankine Cycle is now used as the main heat recovery working fluid, there are trade offs between the compression work and the latent heat of evaporation. The heat recovery cycle is a serial process; therefore, the Rankine working fluid provides additional residual energy that can be recovered by another smaller fraction of the Rankine working fluid. The whole process requires the Rankine Cycle to recover the exhaust heat at its maximum capability and at as high a temperature (superheat) as possible. Mathematically, that is a conflicting requirement imposed on the Rankine working fluid. Also it is a unique condition where the efficiency of the cycle has the highest value (a peak efficiency point). Since the turbine has to satisfy all the ambient conditions (such as temperature, humidity, altitude and loading), the optimized peak forms a unique trajectory as the control path. While mathematically feasible, trying to reduce it to practice became the challenge of the systems development, since the cycle used two working fluids at ambient conditions. Originally this cycle was called the Dual Fluid Cycle. After the initial success of reducing the cycle to commercial use, other scientists including Dr. Urbach [ref.1], called the peak efficiency point the Cheng point (Figure 1). Boyen [ref.2] called the cycle the Cheng Cycle, followed by other authors of thermodynamic books [ref.3]. Thus the name Cheng Cycle was born.

Among many combinations of gaseous and liquid working fluids, one option is helium (a gaseous working fluid with high gamma function) and ammonia (an organic liquid with relatively low latent heat). When engineering economics are considered as design parameters, nothing beats air and water as the most practical working fluids. The right combination of air and water creates a peak efficiency point. It can be found that the peak efficiency is temperature and cycle pressure dependent. Therefore, a path linking all the peak efficiency points as a control trajectory is engine dependent. If funding is no object, a turbine designed from scratch should yield the best efficiency.

NOMENCLATURE

BTU	British thermal unit
cm	centimeter
CLN	Cheng low NOx
CO	carbon monoxide
CPS	Cheng Power Systems
deg F	degrees Fahrenheit
DLN	dry low NOx
GE	General Electric
GM	General Motors
HRSG	Heat Recovery Steam Generator
Hz	hertz
ISO	International Standards Organization
kW	kilowatt
MW	megawatt
NOx	nitrogen oxide
PG & E	Pacific Gas and Electric
ppm	parts per million
R & D	research and development
rpm	revolutions per minute
STIG	steam injected gas turbine
UEM	Universal Electric Machine
US	United States

The Development of the Cheng Cycle, 1974-1984

During the 1970's the oil embargo created the first energy shortage in the US. Suddenly energy conservation became the focus of US energy policy. In the mean time, awareness of the environment due to acid rain put a damper on coal power plants. The dependence on nuclear power looked good for a while until the Three Mile Island incident put that option down. The development of the gas turbine based Combined Cycle became the focus of industrial and government attention. It was so fashionable that even a little 800 kW Solar Saturn gas turbine with a simple cycle efficiency of less than 20 percent had a Combined Cycle version. The US Navy was pushing the Combined Cycle for use on ships. Until the Combined Cycle actually was built, the user's group did not find out that the Combined Cycle had the complexity of a full fluid steam cycle. In addition the Combined Cycle made a good base load power plant, but it was unable to perform in load or partial load operation as promised. The slow startup of a steam cycle made the Navy warships lose the quick start up and go capability of simple cycle power plants. The development of the Cheng Cycle seized the opportunity to commercialize on its new turbine cycle.

It looked good on paper, but it was difficult to make a real engine out of the Cheng Cycle. The first order of business was to determine the cycle parameters and hardware characteristics required to make the engine function to suit the user's needs.

The parameters identified were

1. Quick start-up and go
2. High partial load efficiency
3. Fast response to load following
4. Clean emissions
5. Low cost
6. Easy operation and maintenance
7. Rapid shut down and re-start
8. Utilize as little real estate as possible

This required a totally different thinking in terms of system integration. The configuration of the Cheng Cycle had to be mechanically simple and interlinked by a fast electronic computer control system. As long as the control response time could be so fast that any global instability could be corrected in time, the instability of a feedback control system would no longer require the individual component to be at stable state. That philosophy was influenced by the X-32 fighter airplane forward swept wing design, which is naturally unstable in flight but controlled by fast computer technology. The development steps were as follows:

Select A Basic Turbine

In 1978, the peak efficiency point was defined experimentally using a Solar T50 gas turbine. Allison turbines of GM was willing to participate in a joint venture development program. The Allison 501KB turbine was selected as the first commercial platform.

Performance Mapping

The performance map was jointly produced with the Allison performance group [ref. 4] and a Santa Clara California Utility was the sponsor and promised end user. The performance map can be seen in Figure 2. The top of the map is the control path for partial load conditions. The map pointed out the advantage of separating the electric power capacity and steam production rate for process if used as cogeneration. The separation of steam and electric production provided users of cogeneration an advantage not previously available to them. This led to the decision to add a duct burner to the turbine, so that electric power could be produced at the turbine capacity limit and steam could be produced independently of the power generation. Such a performance map can be seen in Figure 3.

Steam Manifold Design

The steam manifold design went through a number of development stages. Initially air bleed ports were used as steam injection ports, but the thrust bearing of the engine overheated. Based on the theory of fluid mechanical mixing, six large ports located between the six combustion cans just ahead of the premixed air inlet were used. Six more large ports on the order of 6 cm in diameter are located between cans two thirds of the length down the burner can, for the purpose of a power boost and cooling for the hot components. Tests showed that the location of steam injection ports influenced the NOx emission rate, but not the power boost or efficiency.

Comparison of Test Results and the Map

The pressure ratio rise was less than theoretically predicted, but the output increased by 70% and the efficiency increased from 28% to 39%. Some time later, after many engine installations, a discovery was made indicating that the map was produced by a simple assumption that the first stage nozzle was choked. However any turbine designed with a 50% reaction method cannot be choked. Only an impulse turbine design could be choked.

Life of Parts under Steam Injection

Due to the nature of single shaft turbines, the thrust bearing was not affected at any time. Running history of over two million hours never resulted in thrust bearing failures.

The doubling of the torque during the test made a permanent distortion to the power take-off shaft, and it had to be reinforced.

Because of the lower pressure rise, the surge alarm system was removed from the engine.

Increasing the exhaust diffuser area by as much as 50% increased the power output from 5.4 MW to 6.0 MW.

Hot parts life had always been used as an objection against steam injection. In today's turbines, all first stage nozzle and blades have internal cooling passages. The heat transfer of transpiration-cooled blades was studied by Professor E. R .G. Eckert [ref.5] as early as the 1940's. Additional work was jointly published with Donoghue and Moore [ref.6]. Steam has a higher heat capacity. When added into the exhaust path this will in fact increase the overall heat transfer coefficient of the hot gas. Steam can also cool the hot parts effectively through the inner paths. To settle the dispute, extensive hot parts' temperatures were surveyed with thermocouples and optical instruments. No substantial change of metal temperature of the first stage nozzle and blades and the second stage nozzle and blades were observed, with and without steam injection [ref.9].

Design of Heat Recovery Steam Generator

During the early stages of experimentation, traditional HRSG designs were not able to keep operating conditions on the peak efficiency path. Based on traditional surface area calculations of the HRSG (discovered by Prof. Eckert), boiling instability could be triggered. Therefore, the HRSG for the Cheng Cycle had to be a variable pressure boiler and the first and second rows of the heat exchanger surface should have all their fins removed.

Because of the delayed action, the once through boiler was not usable. Most gas turbine compression ratios are under 20 to 1 (below 20 atmospheres), where the boiling temperature varies more with pressure. A combination of lowering the exhaust temperature and raising the HRSG drum pressure can effectively produce a variable heat transfer HRSG utilizing the sensitivity of the pinch point temperature.

The steam flow control valve was moved from the traditional superheater outlet to between the evaporator and the superheater. The advantages were that the superheater would not be subjected to pressure variation and steam from the HRSG could be as close to the exhaust temperature as possible, for greater thermodynamic potential.

System Integration

Adding a low cost, low pressure HRSG would be cheaper than adding a Simple Cycle to double total plant power. The Cheng Cycle could dominate the future power turbine market since it could be sold at the Simple Cycle price with Combined Cycle efficiency. Steps were taken to further reduce redundant component costs. The exhaust bypass gate and the steam injection skid were removed. With proper material selection, the superheater section could run dry, thus operating as simple cycle cogeneration. A bleed valve at the bottom of the superheater was used to blow down and clean up any debris left from previous runs for a period of 30 seconds. Since the superheater was connected to the turbine engine, hot compressed air was blown back through the steam piping. Thus the superheater was cleaned and the steam piping was warmed up to engine skin temperature.

Control System

Computer control technologies were thoroughly explored. The Cheng Cycle control system consisted of several levels. Gas turbines and HRSG's had their respective independent control modules. A supervisory control oversees the function and coordinates all the necessary control functions of the plant. The control screen displays the necessary numerical values of the plant and also animates the function of the plant components. For instance, the water level of the steam drum goes up or down as a function of steam demand and drum conditions. The on or off stand-by pump was depicted in color codes. Up to 18 layers of information can be called upon to check operating and maintenance records. Operating data (including emission records) are trended and permanently recorded. The plant incorporates push button start and shutdown. Power on line can be obtained within the simple cycle full load time domain. Operating sequences are all programmed into the control system.

The first commercial Cheng Cycle was built on the San Jose State University campus to supply electricity and steam for power, heating, and cooling. Surplus power was sold to PG&E.

A sketch of the Cheng Cycle plant can be seen in Figure 4. That plant has 18 years of history on average with over 8200 hours a year of operation. Availability level is over 99%. Since that time over 100 Cheng plants were built around the world.

First Licensed Cheng Cycle Product Kawasaki M001ACC

The Cheng Cycle with Allison 501 gas turbine had been installed in many countries around the world. In California alone there were ten units. This success attracted the attention of the Japanese so the next turbine to adopt the Cheng Cycle process was the Kawasaki M001ACC.

The system was bigger than the Garret 831 but it had similar configurations of a back-to-back centrifugal compressor and a reverse flow combustion chamber. Under license, Cheng Cycle technologies were transferred to the Kawasaki Company to produce their Cheng Cycle version (M001ACC) which increased its output power from 1.5 kW to 2.3 kW with an efficiency increase of nearly 40%. The system configuration was similar to an Allison 501KH. Many units have been installed in Japan for small cogeneration operations, with the first unit being installed in Osaka at Kawasaki's industrial plant.

The Kawasaki M001ACC had a unique steam injection manifold provided by the Cheng process as seen in Figure 5.

1984 to 1994, Development of Free Turbine Type of Cheng Cycle

Gas turbines can be separated by their mechanical configurations into single-shaft, multiple shaft, and free turbine types. For single-shaft gas turbines, the compressor and turbine are on the same rotor. Typically, single-shaft gas turbines are used for power generation applications that run at constant rpm. A two-shaft machine is called an aircraft derivative machine, with a few exceptions of industrial turbines for pumps and marine propulsion applications. Those gas turbines have the advantage of independent rpm between the compressor and the power turbine. Free turbines refer to a combination of high and low pressure turbines. The high-pressure turbine is mounted on the same rotor as the compressor and draws only enough power to drive the compressor. The low-pressure turbine rotates free of the high-pressure turbine and extracts useful work.

The conversion of the free turbine into the Cheng Cycle was different than the experience of the single-shaft turbine. The coupling of the high-pressure turbine to the low-pressure turbine was done through thermal processes and fluid mechanics. This kind of coupling was considered to be soft coupling. The power split between the high-pressure turbine and the low-pressure turbine was designed for simple cycle only. When steam was injected into the combustion chamber, the balance of high-pressure and low-pressure had to be shifted to reestablish a new match. In general, the core turbine had room to accommodate small increases in operating rpm. Beyond that, the core turbine would run into over speed. Slightly opening the core turbine nozzle and slightly closing the low-pressure turbine nozzle shifted the high-pressure and the low-pressure power balance. This was necessary since steam injection increased the power efficiency of the core turbine but no increase in load was required. The percentage of the area of the opening and closing of the turbine nozzles depended on the engine parameters. Our study began in the laboratory on a helicopter T65 engine. Our attempt was to understand the nature of the thermo-fluid interaction in free turbine operation with massive steam injection.

Conversion of T65 Free Turbine

Conversion of the T65 free turbine into the Cheng Cycle was an R & D effort funded in house in order to learn the particular characteristics of free turbine engines and to implement the Cheng Cycle. A picture of the T65 free turbine engine can be seen in Figure 6. The engine had an axial flow compressor stage followed by a centrifugal compressor. A two-stage high-pressure turbine running at 63,000 rpm powered the compressor. Next was the diffuser section where thermocouples were located to measure the low-pressure turbine inlet gas temperature. A single-stage power turbine could be mechanically coupled through a 10:1 gearbox, with a top speed of 6000 rpm. The engine was designed originally for helicopter applications. The combustion chamber was configured in a toroidal shape. The flame sheet was located perpendicular to the shaft of the core turbine. 32 dilution holes were located on the very top of the toroidal shape to provide dilution air into the combustion chamber. Steam injection nozzles were mechanically formed to inject steam through the dilution holes. A concentric steam manifold was added to the combustion wrapper similar to the Allison 501KH as a main steam header. A single steam input flange provided steam supply with a baffle following the steam supply pipe hole to provide uniform distribution of steam flow throughout the 32 steam nozzles.

A stainless steel finned superheater coupled with a copper finned, evaporator waste-heat boiler was connected to the two exhaust manifold ports. The engine (as a simple cycle free turbine) had a thermal efficiency of 19% and a power output of 250 hp. A water-cooled Go-Power dynamo, capable of 6,000 rpm and absorbing 500 hp, was used as the load for the turbine.

The experimental results indicated that the engine was capable of doubling its power output to 500 hp with an increase in thermal efficiency from 19% to 27.5%. The core turbine speed was increased from 94% to 98% designed corrected speed. The engine was temporarily capable of running over 100% speed for helicopter take-off and military power. Due to the high risk involved for over speed operations, the experimental test was stopped at 98% rpm. The engine had no change in nozzle areas. The power turbine inlet temperature was found to be 180 deg F below its maximum operating temperature. In conclusion we believed that with the change of nozzle area, substantially better performance was still obtainable.

LM2500 Cheng Cycle

From 1984 to 1994, GE introduced the steam injected LM2500 and LM5000 (called STIG). STIG design required a steam injection skid and a manual HRSG steam flow control. Furthermore our survey showed most of the installations were for base load operation with a certain degree of difficulty in load following.

In 1994 after the T-65 test results were shown to the GE Aero Division, a joint development program with GE Aero Division and Stewart Stevenson was established to explore the feasibility of a Cheng Cycle for the LM2500PH turbine. If successful, Cheng Power Systems (CPS) would undertake the system integration role to produce a load following LM2500 Cheng system. A system diagram can be seen in Figure 7. GE modified the core turbine and the power turbine area. The STIG efficiency was boosted from 37.8% to 44.8%. CPS developed the control package. The mechanical packaging of the generator set was the responsibility of Stewart Stevenson. The waste heat recovery HRSG was designed and priced by CPS. Since 1998 this product has been ready for the niche market of high efficiency turbines under 30 MW.

1994 to now, Development of Industrial Gas Turbines

Industrial gas turbines require high capital intensity and years of preparation to produce. To influence the improvement of the industrial turbine market, Cheng Power Systems (CPS) was formed in 1994 to implement the Cheng Cycle on retrofit packages of existing gas turbines. The most popular utility turbine was the GE Frame 7 type of gas turbines that include Frame 7B, 7E and 7EA. Figure 8 is a cross-sectional view of a GE Frame 7. The similarity between Frame 7 and Allison 501KH was obvious. Retrofit kits [ref.12] of GE frame engines were developed to boost the power and efficiency of GE frame engines. A majority of them were used in peaking or cogeneration applications. The efficiency of the frame engines could be boosted in a similar fashion as the Allison 501 engine. Therefore the retrofit of GE frame engines provided a low cost option to improve the efficiency and output of a pre-owned simple cycle turbine at a fraction of the new engine cost, usually within the current operating permit at a substantially lower heat rate and with cleaner emissions.

From 1999 to the present time, CPS has developed a low emission combustion system called Cheng Low NOx (CLN) [ref.10]. CLN has a substantially lower pressure drop in the combustion chamber over the dry low NOx system (DLN) and keeps the emissions of NOx and CO simultaneously within the lower single digits in ppm.

Future Outlook of Cheng Cycle

CPS has obtained venture capital funding to project the future of the Cheng Cycle performance for new gas turbines. Efforts have been made to investigate a number new gas turbines which include Kawasaki L20, GE frame 6FA, Westinghouse 501F, and GE frame 7H. The Cheng Cycle [ref. 1,7,8] has survived 25 years of competitive market penetration. This is due to its proven reliability, longevity, low maintenance, low emissions, ease of operation, and a cost level similar to simple cycle with combined cycle efficiency. The following is a summary of the projected engine performance of future Cheng Cycle power plants.

Potential for Kawasaki L20A Cheng Cycle

The L20A gas turbine is the cheapest high efficiency 20MW class gas turbine available for the early 21st century. It is a single-shaft gas turbine operating at 9300 rpm. The pressure ratio is on the order of 18 to 1 with only 11 stages axial flow compressor. The turbine is F class in its firing temperature. The Universal Electric Machine (UEM) [ref.13], developed by CPS eliminates the need for a gearbox for this turbine and can provide 50 or 60 Hz of electrical power with a single package design, with only a flip of a switch. Using the UEM both as a generator and a starting motor simplifies the mechanical package further and eliminates the gearbox loss. Comparison of the performance for its simple cycle operation versus the Cheng Cycle version can be seen in Table 1. The L20A Cheng Cycle can reach 50% efficiency with 30+ MW in power, which is better than any combined cycle in its power class.

Prospect of GE 6FA Cheng Cycle

The GE Frame 6FA is a newly developed engine using F technology to replace the aging Frame 7EA as the future utility-size peaking unit under 100 MW. It has a front-end takeoff configuration with an output of 72 MW at ISO conditions. If the turbine were converted into the Cheng Cycle, the gearbox would be eliminated assuming the generator is a Universal Electric Machine. By doing so, it immediately picked up 2 % in efficiency. The simplicity of the 6FA design consists of 6 combustion cans. Forced by emission constraints, the combustion cans are DLN high-pressure loss devices. With steam injection, the system can revert back to CLN low-pressure loss combustors; the efficiency would improve even further. Comparison of its simple cycle performance to its Cheng Cycle performance can be seen in Table 2.

Westinghouse 501F Cheng Cycle

CPS initially joined an investigation with Westinghouse (now Siemens), into the advantage and limitations of the 501 F turbine. The front-end takeoff design was impressive. The conversion of the 501 F into the Cheng Cycle would involve increasing the flow area of the tailpipe diffuser cross-section, similar to what was done on Allison 501 KH. The conversion into the Cheng Cycle will reach 52% in thermal efficiency and 314 MW. This would be a candidate for a 200+ MW class machine for the future. Comparison of a simple cycle and Cheng Cycle can be seen in Table 3.

Breaking 60% Efficiency Barrier with GE Frame 7H Cheng Cycle

The most impressive advance in gas turbines is the GE frame 7H machine. It has a high firing temperature and has the highest compression ratio of any utility size machine. Those parameters are favorable for a Cheng Cycle conversion, especially since the H machine already requires steam cooling of its first stage turbine. Assuming the use of a UEM power generation system, the current startup system of the H turbine can be substantially simplified. Due to the simplicity of the Cheng Cycle and the high-pressure ratio and temperature of the H turbine, conversion of frame 7H into Cheng Cycle will reach 60.5% in efficiency, which is half a point better than the combined cycle version of the H machine projected by GE. Many more improvements still can be made to reduce the pressure drop of combustors, and system related accessories, better than 60.5 % may still be obtainable. Comparison of a simple cycle and Cheng Cycle can be seen in Table 4.

Conclusion

The Cheng Cycle is the most thermodynamically efficient cycle over the combined cycle and many other proposed variations. However the best Cheng Cycle performance depends on choosing the right parameters in terms of compression ratio, turbine inlet temperature, and simplicity in compressor and rotor configuration. Unfortunately, the combination of the best parameters for the Cheng Cycle is rare because current gas turbines are designed to optimize the thermal efficiency of combined cycles. The recent development of future engines such as L20 and F7H machines demonstrate that they can be more efficient than combined cycles. From a mechanical engineering point of view, simplicity translates into reliability, low maintenance, and flexibility in operations; most certainly lower cost. The authors believe that eventually the Cheng Cycle will be the dominant thermal conversion cycle for utilities, especially if the cycle can be linked to low BTU coal gasification. This presents another cheap alternative for countries such as China, Poland, Germany, and France. With the growing demand of electricity, the Cheng Cycle can be the vehicle to build up the infrastructure for rapid growth in distributed power, instead of vast expensive transmission lines for developing countries.

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Figure 1. Work done by Urbach [1] showing Cheng Point (peak efficiency point) of the Cheng Cycle

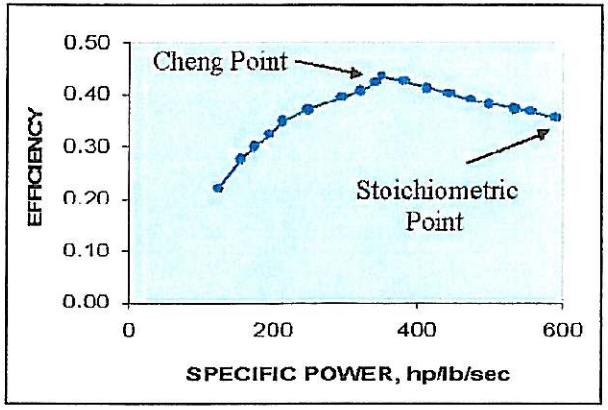

Figure 2. A performance map of Allison 501KB turbine with Cheng Point trajectory

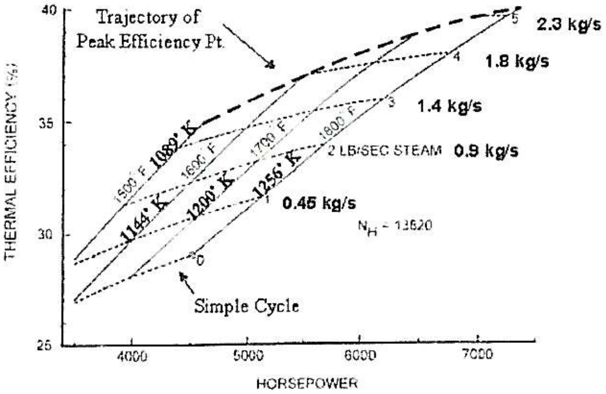

Figure 4. Schematic of Cheng Cycle plant at San Jose State University

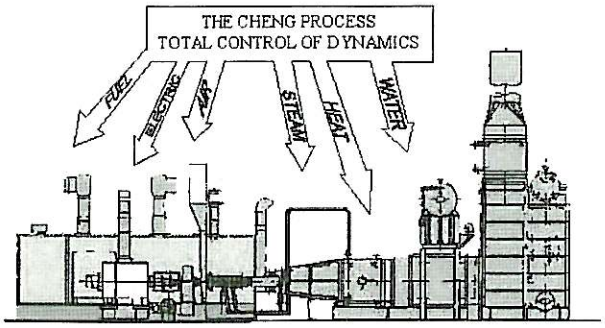

Figure 3. Additional steam generated by adding duct burner to Cheng Cycle Allison 501KB turbine (area shown A above points 3 to 4)

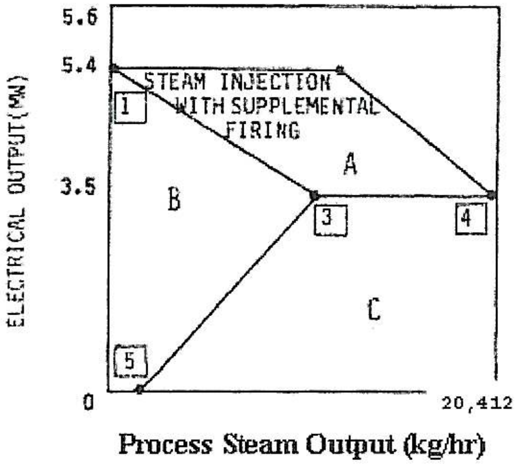

Figure 5. Steam injection manifold for Kawasaki M001ACC turbine

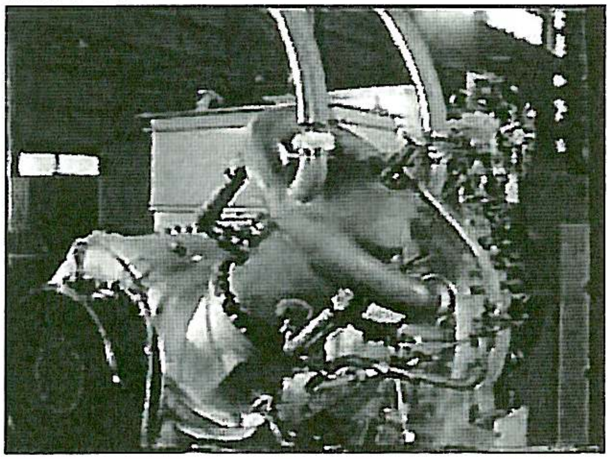

Figure 6. Picture of T65 free turbine converted to Cheng Cycle

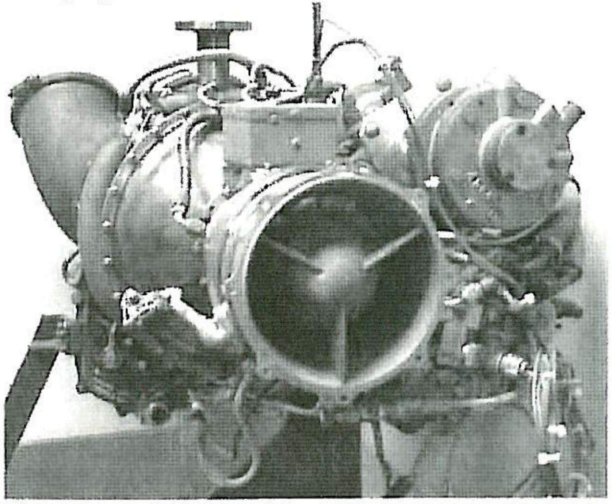

Figure 7. LM2500PH turbine mass flow and component diagram

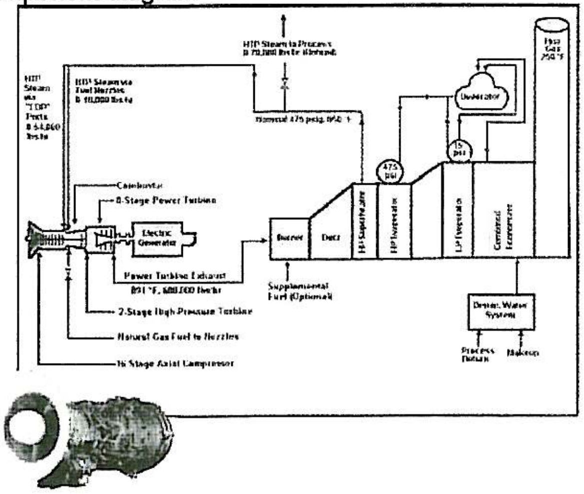

Figure 8. Schematic of GE Frame 7 Engine that can be converted to Cheng Cycle [10,11,12]

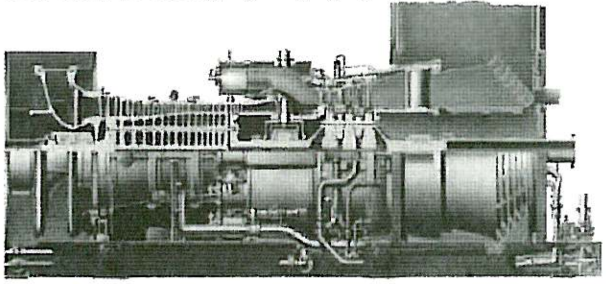

Table 1. Predicted Cheng Cycle performance for Kawasaki L20A gas turbine engine

Kawasaki L20A			
		Simple Cycle	Cheng Cycle
Output	(MW)	18.8	39.5
Heat Rate	(kJ/kWh)	10300	7200
Efficiency	%	35.0%	50.1%
Pressure Ratio		18.0:1	23.5:1
Air Flow	(kg/s)	57	57
Steam Flow	(kg/s)	0	12.2
Turbine Inlet	(deg C)	1250	1250
Exhaust Temp	(deg C)	545	590

Table 2. Predicted Cheng Cycle performance for GE 6FA gas turbine engine

GE 6FA			
		Simple Cycle	Cheng Cycle
Output	(MW)	70.1	131
Heat Rate	(kJ/kWh)	10500	7670
Efficiency	%	34.2%	47.0%
Pressure Ratio		15.0:1	19.0:1
Air Flow	(kg/s)	205	205
Steam Flow	(kg/s)	0	46.7
Turbine Inlet	(deg C)	—	—
Exhaust Temp	(deg C)	589	606

Table 3. Predicted Cheng Cycle performance for Westinghouse 501F gas turbine engine

Westinghouse 501F			
		Simple Cycle	Cheng Cycle
Output	(MW)	177	314
Heat Rate	(kJ/kWh)	9740	6930
Efficiency	%	37.0%	52.0%
Pressure Ratio		14.0:1	19.5:1
Air Flow	(kg/s)	447	434
Steam Flow	(kg/s)	0	91.6
Turbine Inlet	(deg C)	—	—
Exhaust Temp	(deg C)	599	546

Table 4. Predicted Cheng Cycle performance for GE 7H gas turbine engine

GE 7H			
		Simple Cycle	Cheng Cycle
Output	(MW)	—	600
Heat Rate	(kJ/kWh)	—	6000
Efficiency	%	—	60.0%
Pressure Ratio		23:1	29:1
Air Flow	(kg/s)	558	558
Steam Flow	(kg/s)	0	130
Turbine Inlet	(deg C)	1430	1430
Exhaust Temp	(deg C)	—	590