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Design and Construction of the First Commercial Cheng Cycle Series 7 Cogeneration Plant

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ABSTRACT

A description is given of the Cheng Cycle Engine and its application to cogeneration based upon the first commercial plant. The paper covers a description of the plant and its components, unique design features, the automatic control system and the plant operational features. Initial operating performance and NOx emission characteristics are cited.

INTRODUCTION

The Cheng Cycle Series 7 Engine represents an innovative new concept in industrial gas turbines. A detailed discussion of the Cheng Cycle, the potential gains in power and efficiency that its application would yield for a number of gas turbine engines, and an example of the performance improvements it offers in cogeneration applications is given in Reference 1.

Three units were installed in two cogeneration plants by International Power Technology, Inc. in 1984. Both plants completed acceptance tests in December 1984, and were in commercial operation in January, 1985. Two units comprise a single plant at Sunkist Growers, Inc., in Ontario, California. The third unit, the first to be placed in operation, is located at the California State University at San Jose. This paper describes briefly the Cheng Cycle Engine concept and characteristics and the San Jose State University cogeneration plant components, design features, operation and control system characteristics and initial performance levels.

THE CHENG CYCLE SERIES 7 ENGINE COGENERATION SYSTEM

An illustration of the Cheng Cycle Series 7 Engine in a cogeneration plant installation is given in Fig. 1. The Cheng Cycle Series 7 Engine consists of an Allison 501-KH gas turbine in combination with a heat recovery steam generator (HRSG) that is closely matched to assure high cycle efficiency. Steam from the HRSG is injected into the gas turbine combustion region to increase the power output of the basic engine. The KH version of the 501 engine incorporates modifications by Allison specifically for operation on the Cheng Cycle. The HRSG unit consists of:

1) a superheater, located immediately downstream of the turbine exhaust diffuser section, to raise the temperature of the injection steam to as high a value as possible before injection. This temperature elevation reduces the amount of additional fuel that needs to be supplied to the gas turbine to raise the temperature of the steam to turbine inlet temperature, and thus enhances the engine heat rate.

2) a secondary combustor, located immediately downstream of the superheater, followed by a combustion duct section. This secondary combustion provides for the production of additional steam either for increased power generation or for process, depending upon the desired operating condition.

3) an evaporator, located immediately downstream of the combustion duct, for steam generation.

4) an economizer, located downstream of the steam generator, and

5) a feedwater heater.

The operating regime of the Cheng Cycle Series 7 Engine Cogeneration application is illustrated in Fig. 2. Point 2 indicates the power generated by the basic gas turbine driving the generator with no steam injection, and the amount of steam for process generated by the HRSG with no heat added to the exhaust gas by the secondary combustor. Under this condition, the superheater operates dry. As steam is directed from process to the gas turbine, the power output of the turbine and of the generator increases along line 2-1, which represents a constant turbine inlet temperature of 1895 degF (1308 degK) the highest allowable firing temperature for continuous duty. At point 1 all of the steam generated by the gas turbine exhaust heat energy is injected into the gas turbine and none is available for process. Use of the secondary combustor expands the operating regime of the cogeneration system from line 1-2 to include the entire area A . Line 3-4

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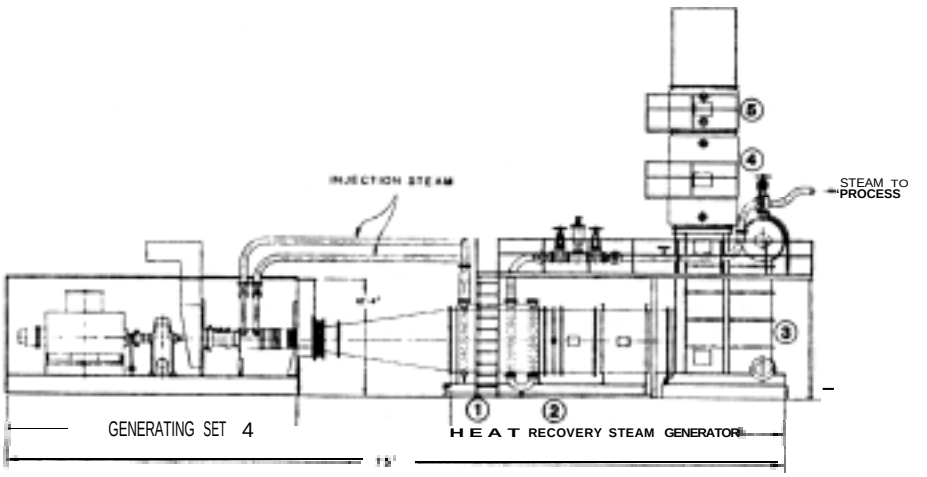
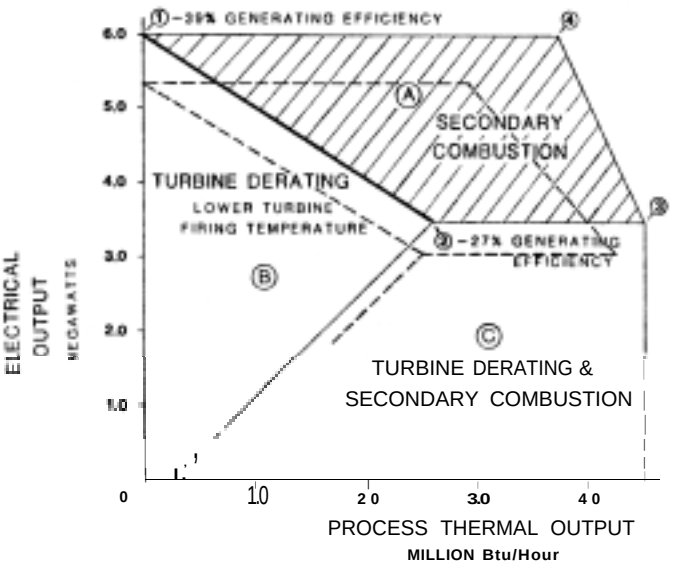


CHENG CYCLE SERIES 7-COGEN PLANT LAYOUT

Fig. 1



CHENG CYCLE SERIES 7-COGEN OPERATING REGIME

Fig. 2

represents firing of the secondary combustor to obtain a temperature of 1600 degF (1144 degK entering the evaporator.

In most cogeneration installations, the process steam demand is given highest priority. If for example, the process steam demand were 20 million BTU/hour, the electrical power output would be limited to about 4 megawatts. If a higher power output were required, firing of the secondary combustor would provide additional steam for injection into the gas turbine to permit the electrical power to be raised to any level up to the maximum of 6 megawatts, while maintaining the process steam flow of 20 million BTU/hour. Alternately, if the process steam demand increased, firing of the secondary combustor would permit the generation of more steam for process, while maintaining the electrical power output of 4 megawatts. Obviously combinations exist to permit operation anywhere within the area A. Operation in areas B and C are possible by derating the gas turbine operation to lower turbine inlet temperatures. In the first commercial installation at the California State University in San Jose, initial operation is being limited to a turbine inlet temperature of 1800 degF (1255 degK and a secondary combustion firing rate to provide a temperature of 1400 degF (1033 degK) entering the evaporator. The operating regimes for this plant are defined by the dotted lines in Fig. 2.

THE FIRST COMMERCIAL PLANT

The first commercial plant completed its formal acceptance tests in December, 1984. The plant is an indoor installation located in a previously unused section of the existing power house at the University that had originally been planned for expansion of the existing plant. A sectional elevation view of the plant is given in Fig. 3, where it may be seen that major components are on a ground level operating floor, with auxiliary equipment in a basement. The primary fuel is natural gas, which is supplied by the local utility at a pressure of 100 to 150 psig. A rotary type gas compressor boosts the pressure to 300+ psig required to supply the gas turbine. The liquid fuel is pumped from underground tanks to an elevated head tank from which it is drawn by a shaft driven fuel pump on the gas turbine. Engine air is drawn from above through ducting into a plenum within the gas turbine-generator set enclosure. The ducting extends down to the basement level and outside to an open subsurface areaway. A self-cleaning filter and an evaporative cooler through which the engine air is drawn are located in this areaway. Cooling air for the generator, gearbox and gas turbine is drawn into the enclosure through a silencer/filter on top of the enclosure, circulated separately through the generator and through the remainder of the enclosure and exhausted through two ducts extending through the roof.

Plan views of both the operating floor level and the basement level are shown in Figs. 4 and 5. The engine inlet air ducting extension may be seen in these Figures and the filter and cooler units may be seen in Fig. 5. The rather abrupt expansion duct section joining the gas turbine exhaust nozzle covering to the superheater is of internally insulated double wall construction and is fitted with a series of turning vanes to avoid flow separation and maintain the pressure

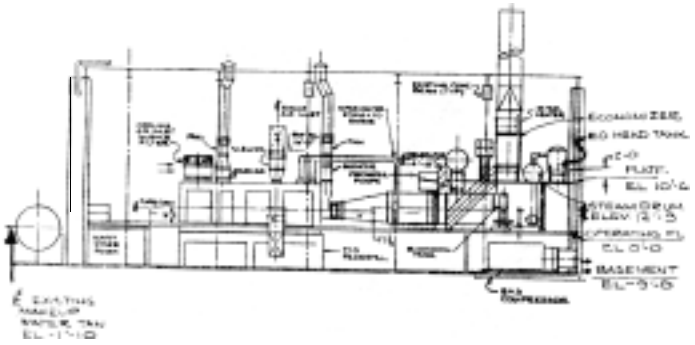


Fig. 3 ELEVATION VIEW, COGENERATION PLANT

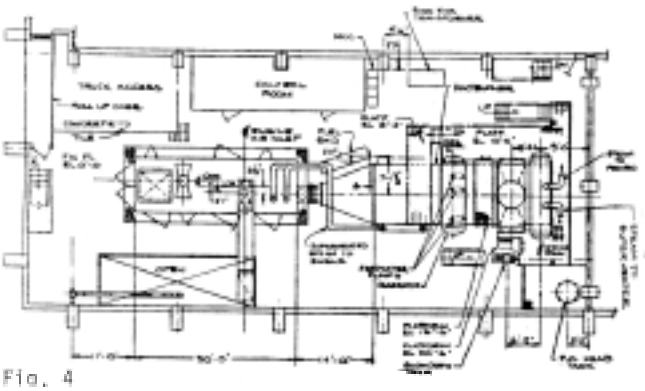


Fig. 4
PLAN VIEW, COGENERATION PLANT, OPERATING FLOOR LEVEL.

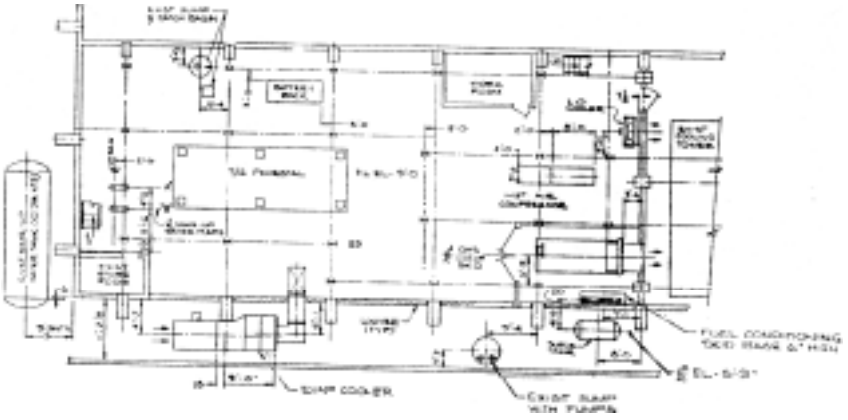


Fig. 5 PLAN VIEW, COGENERATION PLANT, BASEMENT LEVEL.

drop of the exhaust gas/steam mixture at the lowest practical value. Photographs taken during the final construction stages and showing the generator set enclosure and HRSG are presented in Figs. 6 and 7. While the gas turbine generator set and the HRSG were designed to keep the external noise levels to within acceptable values, the plant control room is sound proofed and air conditioned. Interconnecting power and instrumentation wiring from the generator set, the HRSG and auxiliary equipment is run in trays beneath the operating floor, leaving a relatively free and uncluttered area around the unit. Cooling fans for the compressed natural gas and for the generator, gear box and gas turbine lubricating oil draw air through heat exchanger units and exhaust into an open cooling tower area. (See Fig. 5 - The cooling towers are used in conjunction with water chillers which provide for space cooling on the campus.)

Steam is generated by the HRSG at a drum pressure of 205 psig (1.413 x 10^6 Newtons/m^2 This pressure is dictated by the need to provide steam for injection into the gas turbine at a pressure of approximately 170-180 psig (1.172 x 10^6-1.241 x 10^6 Newtons/m^2 allowing for pressure drops through the line, flow control valve and the superheater. Steam is supplied to the University's steam header at a pressure of 50 to 100 psig (3.447 x 105 to 6.894 x 105). The steam supplied to the University is used for space heating and cooling in buildings throughout the campus. An existing underground steam distribution system is used for heating. In summertime, steam is used as the energy source for water chillers. The chilled water is distributed to the University building's air conditioning units. Existing fired boilers will be placed on standby and used to provide steam during periods when the cogeneration plant is down for maintenance or overhaul.

Electrical power is generated at 12.47 KV, the voltage of the main electrical bus, and the generator is tied through a protective breaker directly to the bus. Electrical energy is supplied to serve the University needs, and excess is exported to the local utility (Pacific Gas and Electric Company) grid. If the University electric demand exceeds the output of the cogeneration plant, the shortfall can be imported from the utility grid. In case the utility grid is down, the cogeneration plant can supply the University as an isolated grid.

The cogeneration plant was installed at no cost to the University. It is owned by a third party and is operated for the owner by IPT Energy Management Corporation. The University has an option to purchase the plant. The prime contractor and Architect-Engineer was Ebasco Services, Inc. of Santa Ana. The developer was IPT-Catalyst, and International Power Technology, Inc., patent holder for the Cheng Cycle, furnished the Generator set and the HRSG, which in turn were built by Valley Detroit Diesel Allison and the Deltak Corporation.

DESIGN FEATURES

The Allison 501-KH gas turbine is a modification of the 501-KB5 to operate with steam injection. Two annular steam manifolds are incorporated in the combustor section casing. The casing, in turn, has holes for steam admittance into the combustion section which is comprised of six cylindrical combustion cans arranged in an annular ring. Superheated steam for

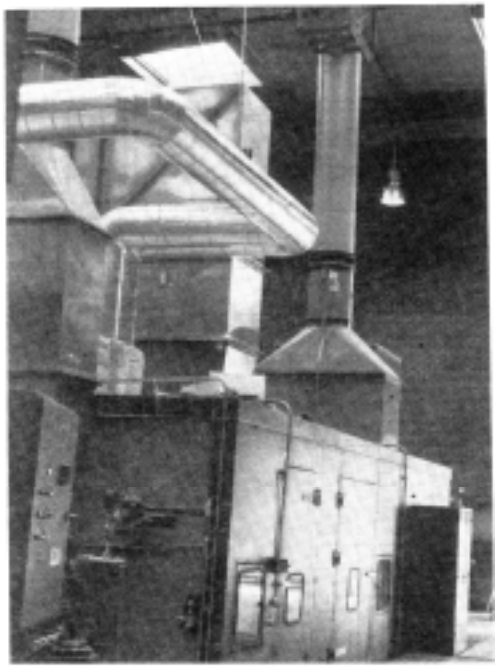


Fig. 6 GAS TURBINE GENERATOR ENCLOSURE DURING CONSTRUCTION.

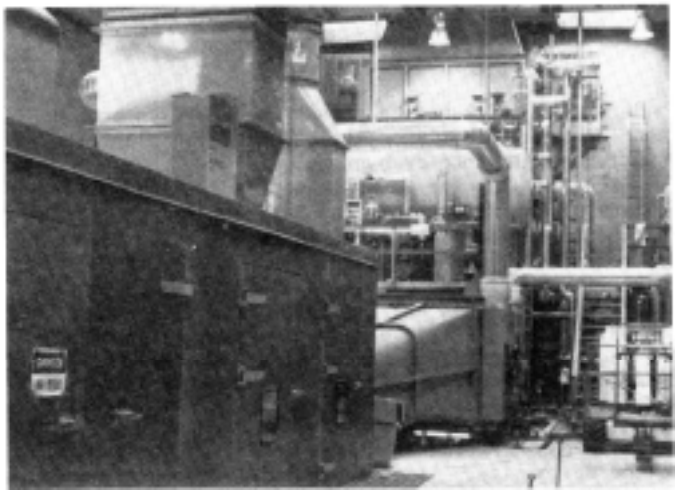


Fig. 7 GAS TURBINE GENERATOR SET AND HRSG DURING CONSTRUCTION.

injection is bought into the gas turbine section of the generation set enclosure by two 6-inch diameter pipes. Each pipe is fitted with a tee section containing a splitter plate and carried to flanged connections on the annular manifolds. There are two flanged connections at 180 deg F on each manifold. The photograph in Fig. 8 shows the two annular manifolds about the combustion section and one of the two steam lines running to each.

A portion of the plant piping and instrumentation diagram is shown in Fig. 9. Upon startup of the system, the gas turbine is brought up to speed at zero load. Once at speed the gas turbine is then loaded to its basic load. As the drum begins steaming, steam begins flowing to the engine as the drum pressure

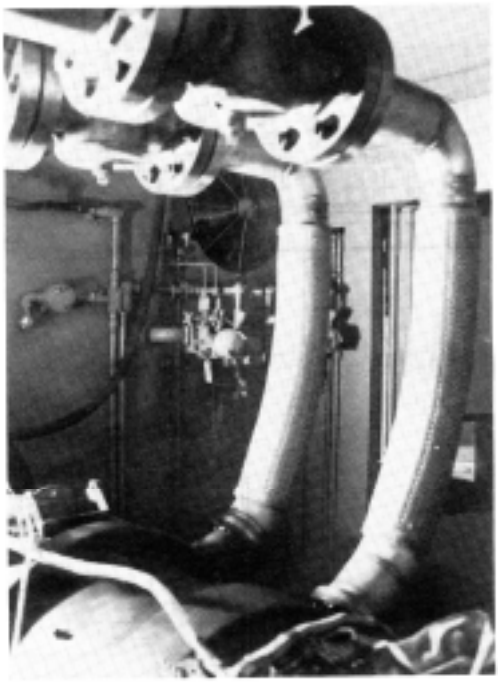


Fig. 8 GAS TURBINE STEAM INJECTION LINES AND MANIFOLD

rises and the steam flow rate is regulated by the injection steam control valve. This concept allows very smooth starts of the Cheng Cycle operation.

The steam drum, as may be noted in Fig. 4, is oversized to provide for greater stability in the water level - a necessity because of the possible rapid and large changes in steam demand as the gas turbine engine responds to sudden electrical demand changes possibly coupled with changes in process steam demand.

The injected steam acts very much like water injection to reduce the NOx production in the gas turbine combustors. The diversion of steam from the downstream to the upstream manifold provides the possibility to enhance the NOx suppression at the lower steam injection rates.

While operation of the San Jose State University plant at the present time calls for firing of the secondary combustor to only 1400 degF (1033 degK) the system was designed for firing to 1600 degF (1144 degK) This was done to allow for possible future increases in steam demand and because 1600 degF (1144 degK) was adapted as a standard design temperature for the Cheng Cycle Series 7 Cogeneration unit. Recognizing the large amount of water vapor in the exhaust stream, special consideration had to be given to the radiation heating from the secondary combustor flame zone to the first rows of tubing in the evaporator. Accommodation to this high heating load (radiation and convection) was made by leaving the first row of tubes bare of fins and providing stainless fins in the second row of tubes.

Concern about the possible deleterious effects of solids carried through the turbine by the injected steam caused special attention to be given to the quality of the feedwater. A large percentage of makeup water must be added on a continuous basis because the steam injected into the gas turbine is not recovered. The carry over from the drum to the steam was held to 0.05%, and because the steam is

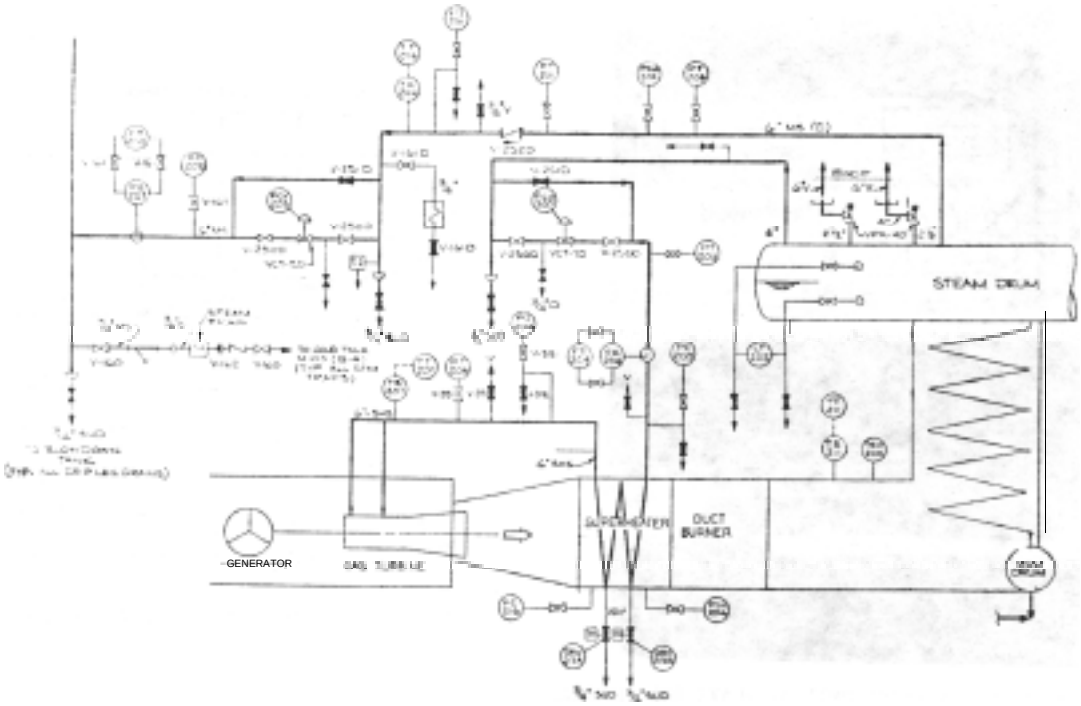


Fig. 9 PIPING AND INSTRUMENTATION DIAGRAM - STEAM AND FEED WATER

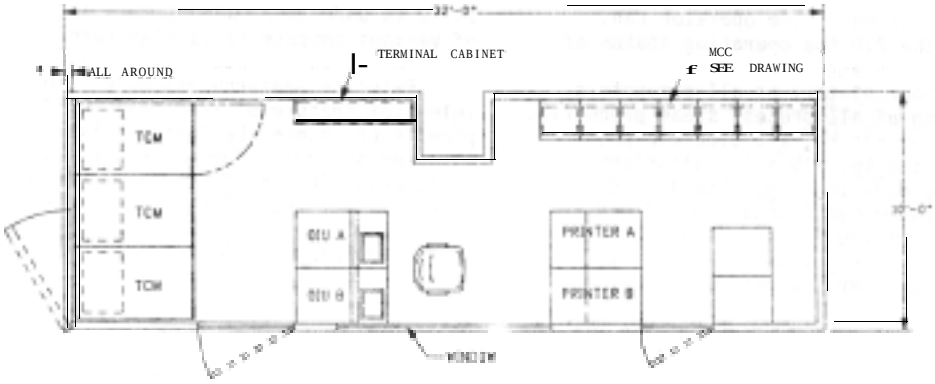


Fig 10. CONTROL ROOM LAYOUT

superheated to over 900 degF (755 degK) in the superheater, it is expected that no water droplets will ever reach the gasturbine. Because the gas turbine will be in operation in excess of 8000 hours per year and a large amount of steam will be injected per year, special treatment of the feed water was undertaken to provide a margin of safety. The raw water at the site contains total dissolved solids (TDS) in the amount of some 520 ppm, and total hardness (as $CaCO_2$) of 400. Reverse osmosis and softener units were provided to bring the makeup water total hardness to less than 0.05 and the TDS down to 40 ppm. A continuous blowdown is utilized to keep the Drum TDS concentration at a relatively low level.

CONTROL

The layout of the control room is shown in Fig. 10. A photograph showing the screens for the Operator Interface Units (OIU) and the Turbine Control Modules (TCM) is shown in Fig. 11. The plant is fully automated and is capable of automatic operation with periodic monitoring by personnel normally engaged in other activities in the power plant building. The automatic control system was supplied by IPT and was developed using Bailey Network 90 hardware components. The first TCM unit houses an annunciator panel and critical operating and safety system parameters. The second TCM unit provides analog displays of the generator and bus operating characteristics as well as protective relays and the gas turbine programmable controller. The third TCM unit contains electrical metering equipment (Jem meters) for billing purposes as well as the electrical synchronizing equipment and the gas turbine governor.

The digital Operator Interface Units supplied by IPT provide upon call-up any information that appears on the TCM panels. In addition it controls the HRSG operation, including the control valve for the gas turbine injection (or Cheng Cycle) steam. Upon call-up it provides status information for the HRSG system and

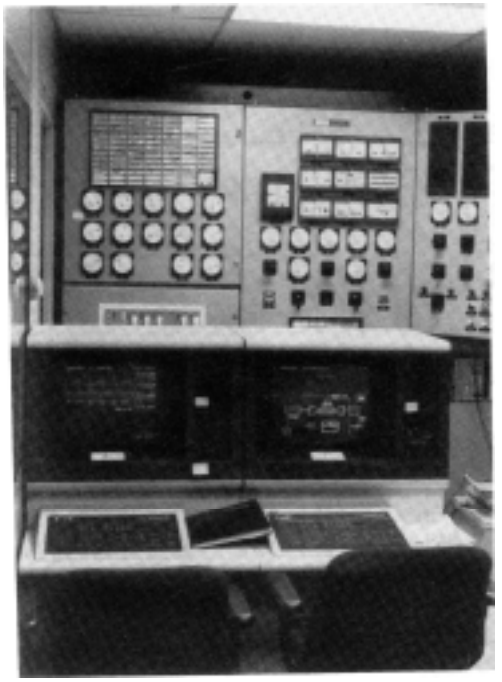


Fig. 11 OPERATOR INTERFACE UNIT DISPLAYS AND TURBINE CONTROL MODULES.

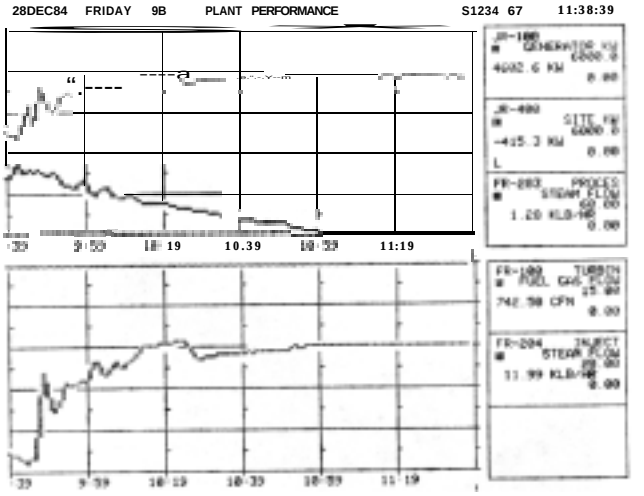


Fig. 12a EXAMPLE OIU DISPLAY PRINTOUT

all balance of plant equipment. The operator can, therefore, call-up on the OIU the operating status of any element of the entire plant and the displays include a complete 26 hour history of all parameters. The OIU provides logging of all process steam production and as back-up to the Jem meters, all electric power production. Either of the two OIU's is sufficient for plant operation and data logging. The second unit is for redundancy to assure continuous control and has data logging. Each of the OIU's have a separate printer for continuous logging of data by periodic printout. Examples of printer records for plant performance, turbine performance, turbine critical parameters and HRSG parameters (taken during the plant test operations) are shown in Fig. 12. There are a total of some eighty displays programmed in the OIU's

INITIAL PERFORMANCE AND EMISSIONS

The Cheng Cycle system is a dynamically coupled system consisting of the heat recovery steam generator (HRSG) and the combustion turbine generator (CTG). The regenerative nature of the injected superheated steam is the key coupling link between the performance of the HRSG and the performance of the CTG. This interdependence allows all components of the system to be operating at their optimal levels, but requires a rapid response control system.

Typical performance is shown in Fig. 13, where it may be seen that the power output was 5321 kw at generator terminals with a turbine inlet temperature of 1879 degF (1299 degK) At this operating condition 19.84 lb/hr (8999.4 kg/hr) of super heated steam was being injected and 49 mbtu/hr of natural gas fuel was being consumed. This performance corresponds to a generator power heat rate of 9210 btu/kwh or power generation efficiency of 37%. The performance data given herein are from initial operation in December, 1984. The plant, while in production operation in 1985, is undergoing adjustments and minor modifications of various components as time permits to tune the plant performance to the peak design levels.

Emission measurements were taken at a turbine inlet temperature of 1800 degF (1255 degK) for plant permitting, since the initial planned operation is at this temperature. The NOx emissions were measured to be about 10 ppm of dry flow (corrected to 15% 02) or about 70 lb/day, for a power production rate of 5370 kw and for process steam ranging from 0 lbs/hr to 25,000 lb/hr by firing of the secondary combustor.

REFERENCE

1. Jones, J.L., Flynn, B.R. and Strother, J.R., "Operating Flexibility and Economic Benefits of a Dual-Fluid Cycle 501-KB Gas Turbine Engine in Cogeneration Applications", ASME paper 82-GT-298, 1982.

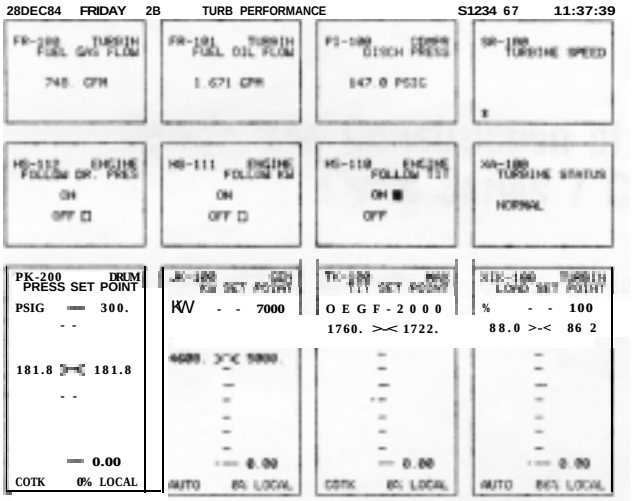


Fig. 12 b EXAMPLE OIU DISPLAY PRINTOUT

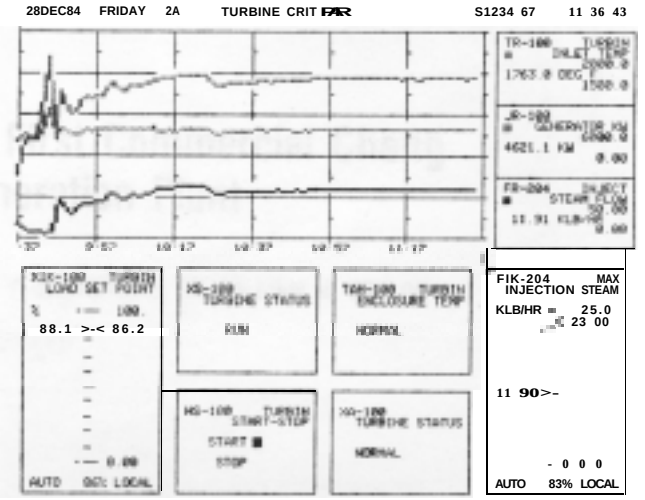


Fig. 12c EXAMPLE OIU DISPLAY PRINTOUT

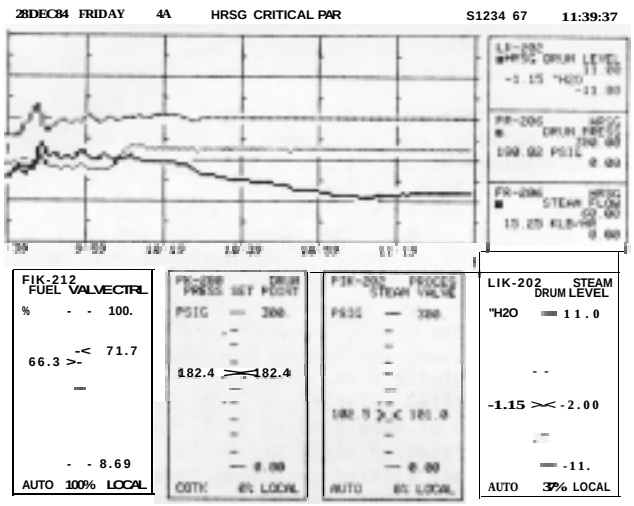


Fig. 12d EXAMPLE OIU DISPLAY PRINTOUT

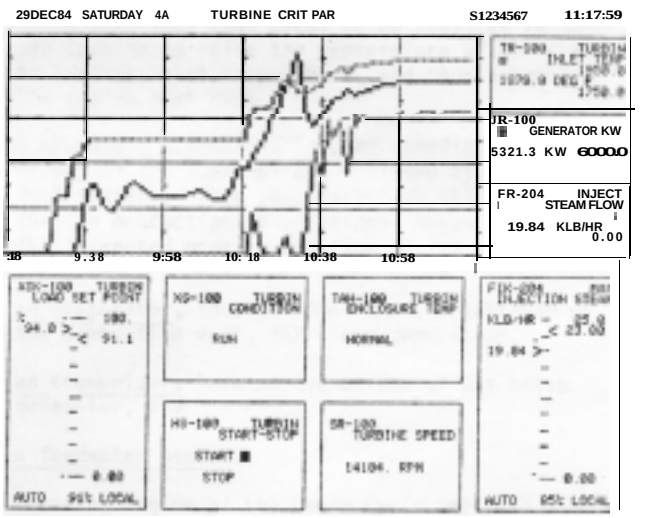


Fig. 13 INITIAL PERFORMANCE