The Cheng cycle offers flexible cogeneration options

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Reprinted from Modern Power Systems
March 1985

International Power Technology

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The Cheng dual fluid cycle involves injecting steam into a gas turbine. The steam is generated in a waste heat boiler on the turbine exhaust. This results in a significant increase in turbine efficiency and may be used as the basis for a flexible cogeneration system. Two such installations are now operating in the USA.

The concept of gas turbine steam injection is not new, experiments having been performed as early as 1905. Until recently, however, use of steam injection had been limited to NO_x control or simple power augmentation.

The critical and interrelated nature of steam to air ratios, steam to fuel ratios, and other cycle parameters in optimising the efficiency of the steam injected gas turbine cycle was first realised by Dr Dah Yu Cheng, a professor of physics at the University of Santa Clara. In 1974, Dr Cheng formed International Power Technology to develop and commercialise his idea. Since that time he has been granted over 60 US and international patents on the concept and associated hardware.

Now called the Cheng Cycle, the concept has gone through a number of development stages, the most recent being commercial application using the Allison 501 gas turbine. The 501 based system, designated the Cheng Cycle Series 7, is currently in operation at two locations in the USA.

The Cheng Cycle uses proven industrial components in a thermodynamically optimised mode. Waste heat energy from a gas turbine is captured in the form of steam using a heat recovery steam generator (see Figure 1). In a pure power generation application, all the steam produced by waste heat is recycled through the gas turbine.

The added mass flow due to the steam produces an increase in work output from the turbine. For the Allison 501 the power output increases by 75 per cent and the thermal efficiency by 40 per cent. The price paid is 19 per cent increase in fuel consumption.

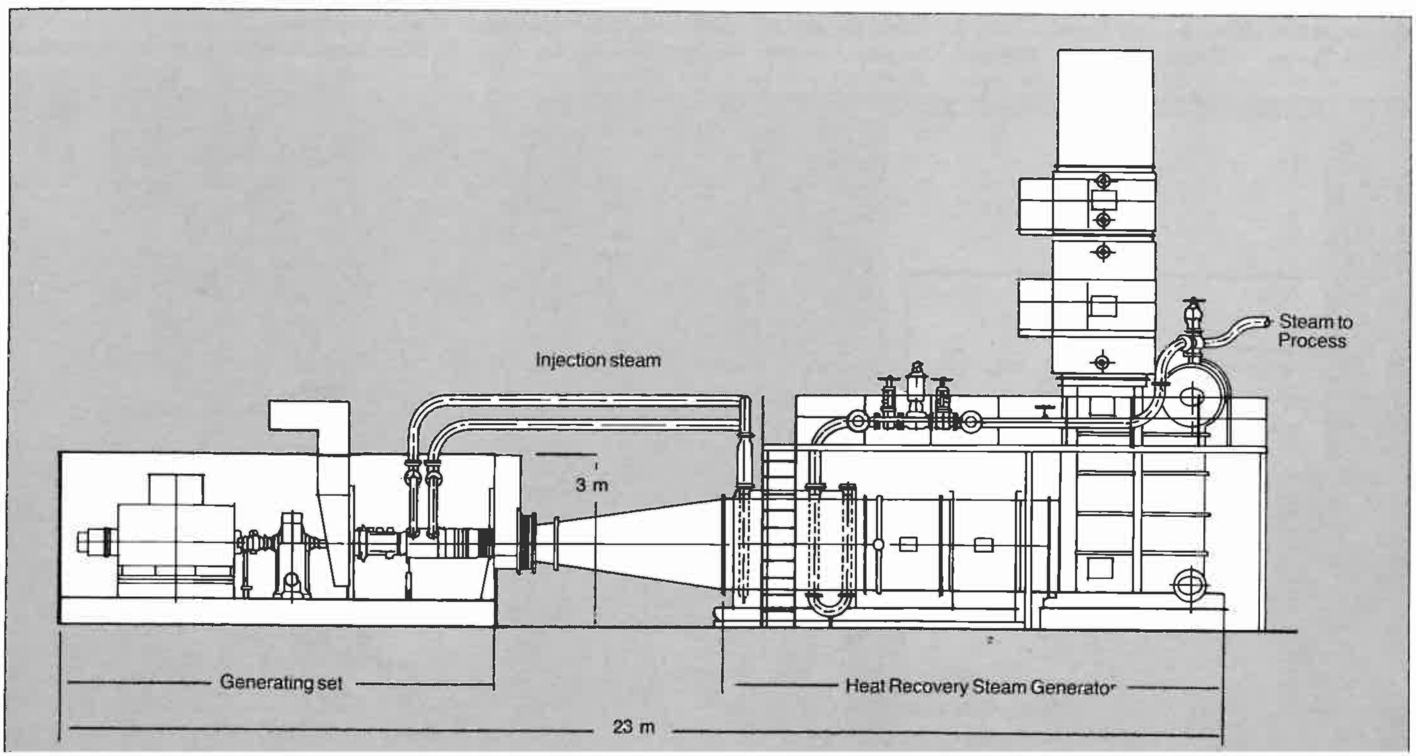
Although simple in concept, the system becomes complex due to feedback effects associated with steam passing through the turbine and in turn generating more steam in the boiler. Additional complexity is added when one attempts to optimise the overall system for maximum efficiency. Trade-offs must be made between mass of steam produced and degree of superheat. The Cheng Cycle, as patented by International Power Technology, maximises overall system efficiency.

In cogeneration applications, the Cheng Cycle system is modified to the extent that steam may either be used for process needs or sent to the gas turbine. The result is a system which combines operating flexibility and mechanical simplicity.

Equipment configuration

The Cheng Cycle system consists of three pre-engineered modular components: a gas turbine generating set, a matched waste heat recovery steam generator, and system controls responsible for coordinating and optimising operation of the system. The flexibility of the system makes it applicable to a wide range of sites with little or no design change in the major equipment package.

The first commercial application of the concept is called the Cheng Cycle Series 7-Cogen. The system is capable of producing up to 6 MWe and 20 430 kg of steam per hour. The 501 turbine is manufactured and modified for Cheng Cycle operation by the



Allison Division of General Motors.

Technical suitability and proven reliability were primary reasons for choice of the 501. The turbine's high surge margin and structural design margins made it ideal for the increased mass flow and power output associated with Cheng Cycle operation.

Development of the steam injected 501, designated the 501-KH, has been a cooperative effort.

The heat recovery steam generator (HRSG) is very similar to a conventional waste heat boiler with two exceptions. First is the addition of a superheater upstream of the evaporator section. Second is the carefully controlled ratio of surface areas between the superheater and evaporator. The Series 7 is also configured for supplemental firing, which greatly enhances operating flexibility. The HRSG is produced by major boiler manufacturers under subcontract.

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

- A supervisory level which controls overall system operations on a real time basis. Decisions at this level are made on the basis of economic optimisation, 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 system (fuel flow, steam flow, etc). This level implements the operating strategy chosen by the supervisory level and ensures that process requirements are met at all times.

The Series 7 control system utilises distributed digital control hardware configured to meet the needs of the Cheng Cycle system and any site specific requirements.

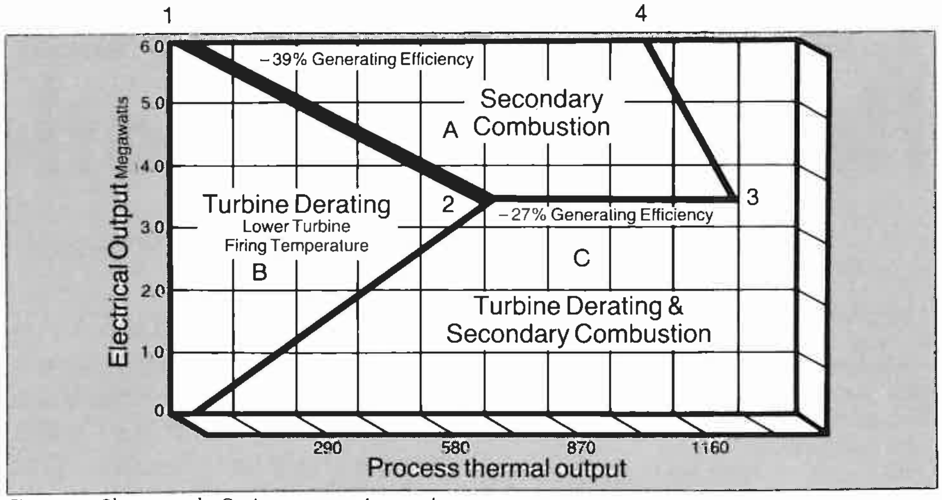


Figure 2. Cheng cycle Series 7 operation regime

Operating characteristics

The Series 7-Cogen operating regime is shown in Figure 2. Line 1-2 indicates power and thermal output for operation at constant rated turbine inlet temperature and various levels of steam injection. At point 2, no steam is injected, and power and thermal output are equal to that of a simple cycle Allison 501 cogeneration plant. At point 1, all available thermal energy is used to produce injection steam; power output and generating efficiency are maximised. It is important to note that turbine operating temperature does not change along line 1-2, only the amount of steam injection.

Region A represents the addition of supplemental firing in the HRSG. This feature allows the system to produce any combination of electrical and thermal outputs within the region. Again, the turbine operates at constant temperature throughout this regime.

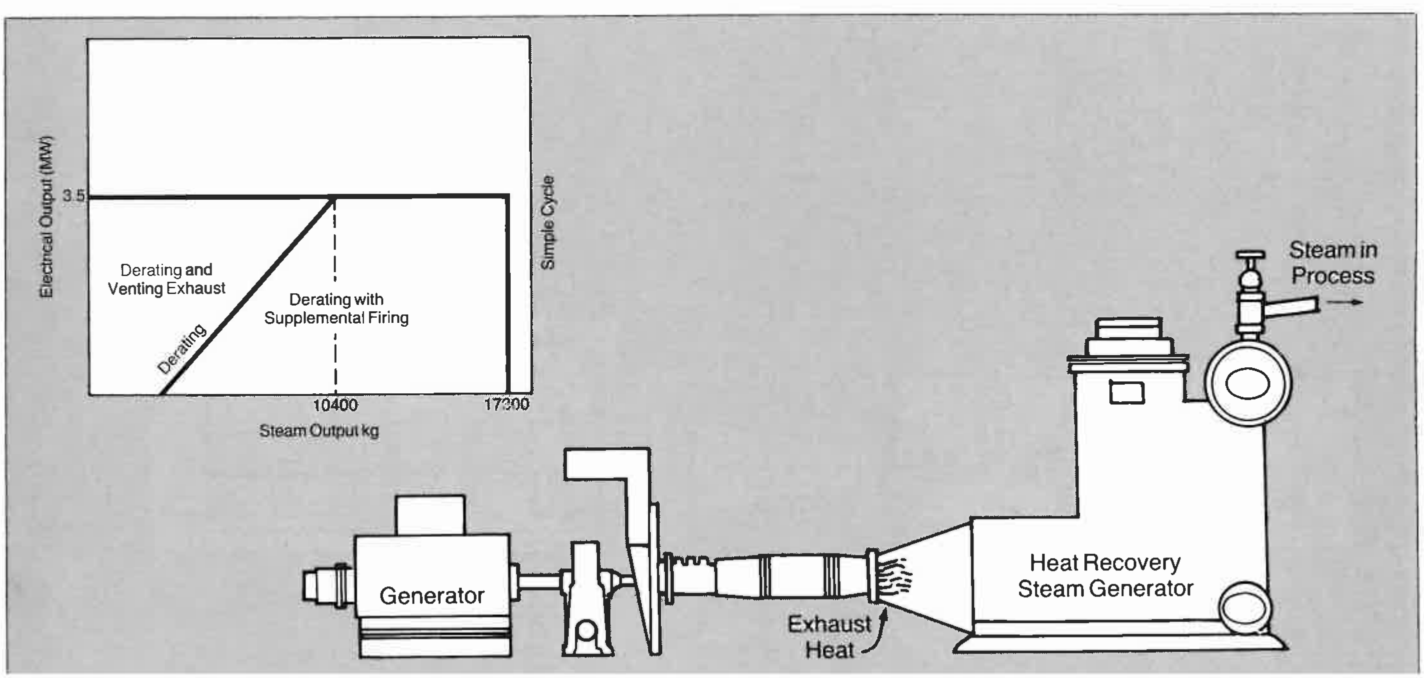
Region B represents steam injection with lower turbine inlet temperature (derating). It can be visualised as a series of lines parallel to line 1-2, each representing progressively lower turbine firing temperatures. Region C represents lower turbine inlet temperatures with supplemental firing and no steam injection.

Reducing turbine inlet temperature increases engine life. It has been estimated that the engine life is doubled for every 27.8°K reduction in turbine inlet temperature.

Modes of operation

The supervisory controls operate the system in the most economic manner. This becomes particularly important because Cheng Cycle flexibility implies a number of operating choices. These choices can be thought of as operating modes, and mode selection depends on load and energy price characteristics.

The most common mode consists of



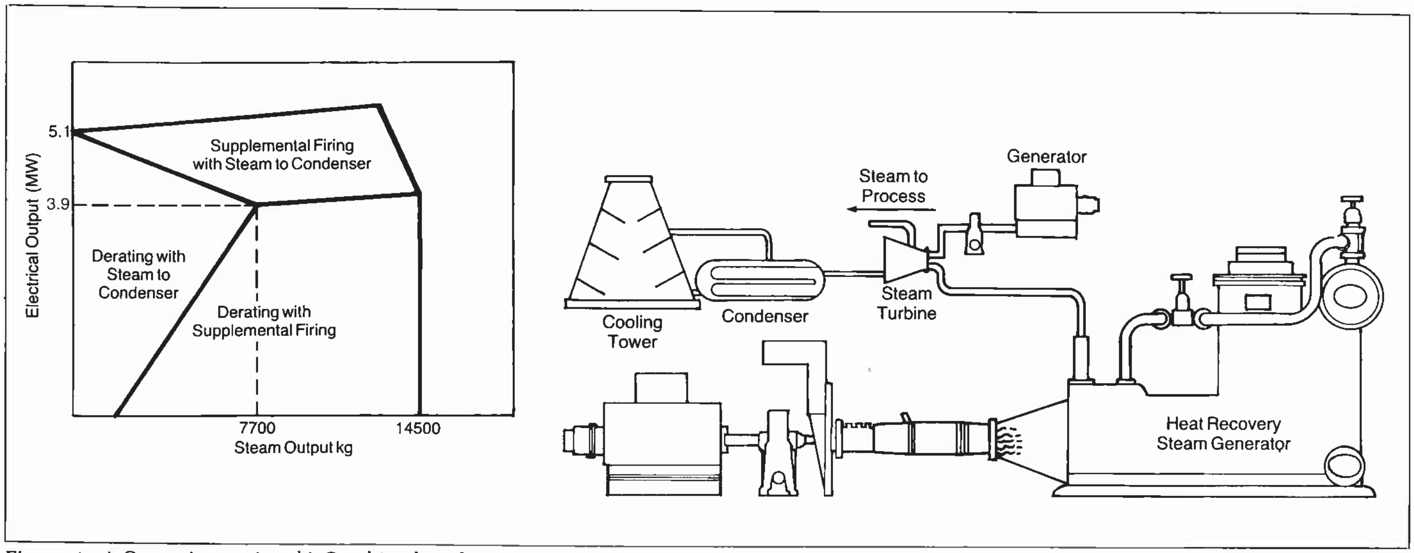


Figure 4. a) Operating regime b) Combined cycle system

operating along line 1-2-3 in Figure 2. The specific operating point is determined by process steam demand, and electrical power output is allowed to float.

The second common mode of operation occurs during periods of high electricity prices. Under these conditions, economics dictate that electrical output be maximised. The system will operate along line 1-4 of Figure 2.

A third mode of operation occurs under conditions such as a utility outage or very low electricity buyback rates. In this mode, thermal and electrical output are matched simultaneously to the requirements of the site. The operating point in this mode could be anywhere in the operating regime (regions A, B, or C in Figure 2).

Steam injection

The fact that the Cheng Cycle system operates most often in a constant firing temperature mode can significantly increase turbine life and mean time between overhauls. As long as the system operates in region A of Figure 2, turbine operating temperature remains constant. Whereas a conventional system will often derate to follow a decrease in thermal load, the Cheng Cycle system follows these fluctuations without derating. Eliminating this thermal cycle can add significantly to turbine life.

Under full steam injection, the power output of the gas turbine is increased by as much as 70 per cent. However, the increase in turbine component stresses is generally much less.

For a simple cycle 501 gas turbine, approximately 70 per cent of the work produced by the power turbine goes to drive the compressor. Since compressor power requirements are relatively insensitive to steam injection level a large increase in net power output requires a much smaller percentage increase in total power turbine output.

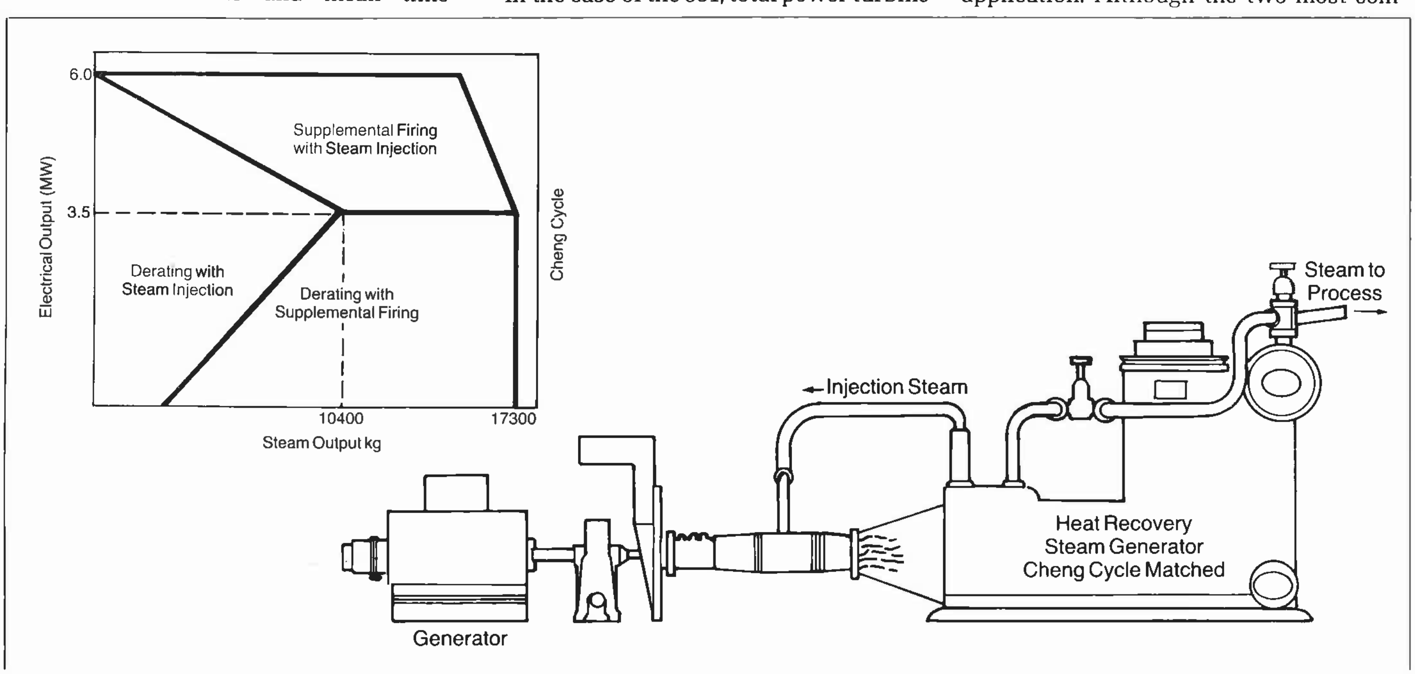
In the case of the 501, total power turbine output increases by only about 20 per cent to achieve the 70 per cent net increase. The Allison 501 turbine possesses more than adequate design margins for this level of increase and little modification is required for steam injection.

Water quality requirements for the system are dictated by the boiler rather than the gas turbine. The Series 7 steam generator nominally operates at a gauge pressure of 14 bar.

At this pressure, carry over of impurities from the drum into the superheater is minimal. Standard guidelines for low pressure boilers are adequate for design of the water treatment system, although the designer will want to assess the trade-offs between blowdown and water treatment costs.

Comparison with conventional cycles

The choice of thermodynamic cycle depends on the specifics of a given application. Although the two most com-



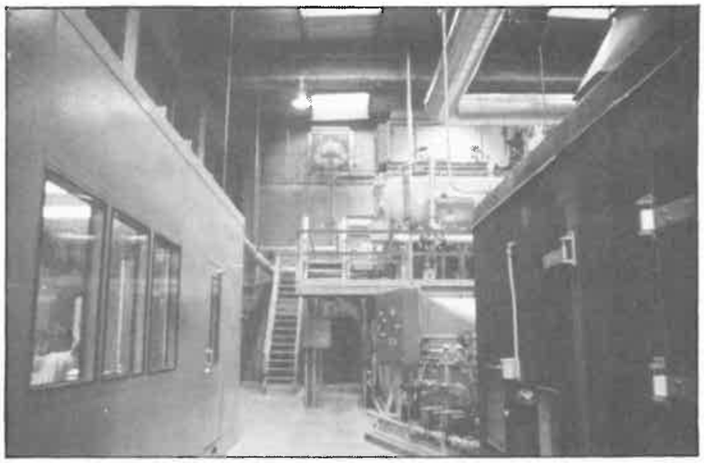


Figure 6. San Jose State University installation

Figure 7. Sunkist growers' installation

monly used gas turbine based systems, simple and combined cycle, have applications where they are most effective, the Cheng Cycle typically offers several advantages.

A simple cycle system (Figure 3a) consists of a gas turbine exhausting into a waste heat steam generator. This is an efficient and economic system for applications with constant thermal loads. However, when thermal load drops below rated design point for significant periods of time the operating economics are severely penalised.

When loads do fluctuate below rated output, two options are available: bypass exhaust around the boiler and reduce steam output, or derate the gas turbine and reduce both thermal steam and electrical output (Figure 3b). High electrical price relative to fuel price favours maintaining electrical output, whereas a lower ratio of these two prices would favour the derating option. However, bypassing the exhaust represents a waste of potentially useful energy, and derating means lowering the output of a large capital investment.

One solution to the problem of variable loads is a combined cycle system. A common configuration consists of a gas turbine exhausting into a steam generator, which in turn sends the steam to a steam turbine (Figure 4a).

The addition of the steam turbine has the effect of providing a more economic alternative than either bypassing the exhaust or derating. Steam not needed for process is expanded through the turbine and condensed, thus producing more electricity (Figure 4b). In many instances, the combined cycle alternative boosts economic returns substantially. However, the system is significantly more complex than the simple cycle system, and results in higher investment and operating costs.

The Cheng Cycle system is similar in its mechanical simplicity to the simple cycle system (Figure 5a). But operating flexibility is much greater for the Cheng Cycle system than for the simple cycle system (Figure 5b). The Cheng Cycle system also offers a broader operating regime and

Commercial applications

Each Series 7 has a steam generating capacity of up to 20 430 kg per hour with supplemental firing. Sites with greater steam requirements can be handled using multiple units. The steam injection capability of the Series 7 means that the lower bound of thermal load is determined by economic considerations.

The applicability of the Series 7-Cogen covers sites with thermal loads ranging from less than 4500 kg per hour to over 45 000 kg. The basic equipment configuration varies little from site to site resulting in lower overall installed costs.

Two sites are in commercial operation at this time. They differ in many respects.

San Jose State University

The San Jose State University installation, in the USA, consists of one Cheng Cycle Series 7 installed adjacent to the University's boiler house (Figure 4). Startup occurred in December, 1984.

The University's energy loads vary widely as a function of both the cyclic nature of University operations and seasonal weather changes. Steam demand varies from a peak rate of over 13 600 kg per hour during the winter heating season to a low of almost zero during the summer. Electrical loads are also highly variable, reaching a peak of over 5 MW with summer air conditioning requirements.

The cogeneration plant is capable of meeting total steam and electrical requirements. When the cogeneration plant is down for routine maintenance, backup is supplied by the University's existing boiler plant and the local electrical utility. Power generated above the University's requirement is sold to the utility at avoided cost rates. When these avoided cost rates are high enough, as during the utility's summer peak hours, cogeneration plant power output is maximised.

The San Jose State University project was financed on a third party basis. This means that the University contributed no capital to the project, but will share in the profits. In addition, the University increases energy system reliability by

tenance of the plant is the responsibility of IPT Energy Management, an International Power Technology subsidiary.

Sunkist Growers

The Sunkist Growers installation, located in Ontario, California, consists of two identical Series 7's (Figure 5). The Sunkist facility processes oranges and lemons from surrounding agricultural areas. Startup of the cogeneration plant occurred in December, 1984.

As with the university application, loads are highly variable. Fluctuations are due primarily to the seasonal nature of the citrus industry, as well as facility operating schedule. The Sunkist facility typically operates 24 hours a day, 5 days a week, with most processes shut down over the weekend. Steam loads vary from almost zero to over 36 300 kg per hour. Electrical loads peak at around 7 MW.

The cogeneration plant is capable of meeting Sunkist's entire requirements. The use of dual units means backup requirements are less critical although backup is available from the local electrical utility and existing boilers.

As at San Jose, excess electricity is sold to the utility. Since cogeneration plant capacity exeeds Sunkist's requirements by about 5 MW, a contract to supply firm power to the utility has been signed. This will require the cogeneration plant to operate at maximum capacity during summer peak hours.

The Sunkist plant is also financed on a third party basis with Sunkist receiving benefits similar to those enjoyed by San Jose State University. IPT Energy Management again has operating and maintenance responsibility.

Future applications

Although current commercial application of the Cheng Cycle has been limited to the Series 7 system in cogeneration, the future holds a number of potential other opportunities.

The Cheng Cycle is applicable to many commercially available gas turbines. Studies are currently under way to