COGENERATION AND WOOD/BIOMASS FUELED POWER SISTEMS

ELIAS P.GYFTOPOULOS

Massachusetts Institute of Technology Cambridge, Massachusetts
U.S.A.

SUMMARY

The purpose of this paper is to describe a number of recently installed cogeneration systems and wood/biomass fuelled power systems. Cogeneration affords one of the largest opportunities for saving fuel because many common processes have sizeable waste energies suitable for this technology. Some of the energy conversion devices, such as steam turbines and reciprocating diesel and spark-ignition engines, have been in common use for decades. Others, such as turbines with organic material as a working fluid and thermionic converters are just now being commercialized or are still undergoing testing. A survey of typical applications is presented with special references to wood/biomass fuelled power systems.

RESUMEN

El objeto de esta ponencia es la descripción de algunos sistemas de cogeneración recientemente instalados y sistemas que utilizan la madera/biomasa como combustible. La cogeneración es un sistema que ofrece una de las mayores posibilidades para el ahorro de energía dado que muchos procesos liberan energía que se puede aprovechar con esta tecnología. Algunas de las unidades de conversion de energía tales como turbinas de gas, motores alternativos diesel o motores de explosion se llevan utilizando desde hace tiempo. Otros como las turbinas que utilizan materia orgánica como combustibles o los convertidores termoiónicos se están comercializando en la actualidad o están en fase de experimentación. Se presenta un conjunto de aplicaciones típicas en este campo con especial énfasis en sistemas cuyo combustible es la madera o la biomasa.

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ELIAS P.GYFTOPOULOS

Massachusetts Institute of Technology Departments of Mechanical and Nuclear Engineering Room 24–109 77 Massachusetts Avenue Cambridge, Massachusetts 02139, U.S.A.

1.
INTRODUCTION

The purpose of this paper is to describe a number of recently installed cogeneration systems and wood/biomass fueled power systems.

As it is well known, the term cogeneration refers to the concurrent generation of motive power or electricity and process heat or steam. Cogeneration saves fuel because either waste energy from a heating process is used for the generation of motive power, or waste energy from a power plant is used for heating applications. Typical fuel savings are illustrated schematically in Figures 1 and 2. For example, the top of Figure 1 shows the fuel consumption—2. 25 barrels of oil (14.2 MJ)—of a high temperature heating process requiring 5.4 million British thermal units of net process heat (5.7 MJ), and the fuel consumption—1 barrel of oil (6.3 MJ)—of a power plant generating 600 kilowatt-hours of electricity. The bottom of the figure shows that the same energy services can be provided by using only 2.25 barrels of oil (14.2 MJ) to fire the high temperature process, and then capturing the waste energy from this process to supply the power plant. Thus, an energy saving of 31 percent is achieved.

Again, the top of Figure 2 shows the fuel consumption—1.75 barrels of oil (11. 1 MJ)—of a low-pressure steam boiler that raises 8,500 pounds (3,860 kg) of process steam, and the fuel consumption—1 barrel of oil (6.3 MJ)— required for 600 kilowatt-hours of electricity. The bottom of the figure shows how the same energy services can be provided using only 2.25 barrels of oil (14.2 MJ). This energy is used in a boiler to raise high-pressure steam, which in turn flows into a back-pressure turbine. The turbine powers the generator, and supplies low pressure steam to the process. Here, the energy saving is 19 percent.

Cogeneration affords one of the largest opportunities for saving fuel because many common processes have sizeable waste energies suitable for this technology.

It encompasses many different energy recovery and energy conversion devices. Some of the energy conversion devices, such as steam turbines and reciprocating diesel and spark-ignition engines, have been in common use for decades. Others, such as turbines with an organic material as a working fluid and thermionic converters, are just now being commercialized or are still undergoing testing. The various conversion technologies currently available and those soon to enter the marketplace provide power system designers and utility managers with an unprecedented opportunity to save not only energy but scarce capital as well.

Small-scale cogeneration facilities save capital because the equipment is built in a manufacturing plant rather than at the site of the facility, and in a much shorter time than that required for a large central electric power station. This latter feature is an invaluable tool for electric utility planners who have had to predict under conditions of great uncertainty electricity demands a decade before a new large power plant would finally come into service.

Power devices for cogeneration fall into two distinct classes: topping units and bottoming units. Topping units take advantage of the fact that many low-temperature direct-fired processes such as drying, curing, baking, space heating, and washing are thermodynamically inefficient because they consume directly the high-quality energy of high-temperature combustion products for tasks that actually require only low-quality energy. The effectiveness of fuel use in such processes can be increased substantially by first using the high-quality energy of fuel combustion in a diesel engine, gas turbine, or steam turbine to drive an electric generator, and then recovering the exhaust energy of the unit to perform heating tasks needing temperatures of only 70 to 350°C. Bottoming units are applicable to high-temperature processes such as the production of metals and ceramics in furnaces and kilns operating at 500°C and above. Waste energy from such a process is directed to a power conversion device driving an electrical generator. In a typical application, furnace exhaust gas, still containing a large quantity of high-quality energy, is directed to a boiler where steam is generated. The steam drives a turbine-generator engine and produces electricity. The combined system uses about 30 percent less energy than when the furnace heat and electricity are produced separately. Cogeneration by means of waste energy recovery with a bottoming engine is particularly attractive because it produces electricity with no incremental consumption of fuel and often can be installed in existing facilities.

Another source of cost-effective contributions to a nation's energy needs is through use of biomass either in cogeneration or power plants. Forests are one of the most valuable and renewable resources. Wood wastes generated from forest management techniques and by-products from wood processing operations can fuel electricity plants. Agricultural wastes in the form of field crop residues, tree and vineyard prunings, shells, pits, hulls, and other general processing waste are also suitable fuels for electricity generators.

2.
TECHNOLOGIES

The major energy conversion technologies used in cogeneration are described briefly in what follows.

Steam Turbines. Steam turbines have been used for both cogeneration and conventional power generation throughout much of this century. In a paper mill, for example, a high-pressure topping turbine extracts part of the energy from a high-pressure steam flow. The remaining energy in the exhaust steam, at pressures of 3 to 15 atmospheres, is used to operate paper mill machinery such as digesters, blenders, and dryers. A typical electrical output would be about 50 kilowatt-hours per million kilojoules of steam energy delivered to the mill machinery.

In a district heating installation, waste energy from a power plant is fed, either in the form of low-pressure steam or hot water, to a network that supplies the heating needs of a city or a residential and commercial complex of buildings.

Low-pressure steam turbines are used as bottoming units. They recover waste energy from relatively high-temperature exhaust gases of a process by means of a waste-heat boiler, or from the spent steam of intermediate-temperature industrial processes.

Steam topping and bottoming turbines are feasible from about 2 megawatts up to several hundred megawatts with presently available hardware. Capital and installation costs for such units range from abut $1000 to $2000 per kilowatt, depending upon system size, waste energy temperature, type of fuel, and specific interface requirements and site constraints for the cogeneration system.

For district heating applications, the capital and installation costs are dictated by the type of plant under consideration and the costs of the district heating network.

Diesel Engines. Diesel engines are applicable as topping units of cogeneration systems when a high ratio of electrical output to process heat is required—up to 400 kilowatt-hours per million kilojoules of heat delivered to the process. Process steam and hot water are produced by recovery boilers coupled to the exhaust stack and to the cooling water of the engine. Systems from as little as 100 kilowatts to several thousand kilowatts can be built. However, these systems are based upon medium-speed and high-speed diesel engines, the type generally used in trucks, construction equipment, and rail locomotives. Such engines are limited to the burning of high-grade distillate petroleum, a product that is likely to be expensive and often in short supply in years to come.

A more versatile diesel engine for topping large cogeneration systems, from several thousand kilowatts up to about 30,000 kilowatts, is the large slow-speed, two-stroke diesel engine. This engine, often used for propulsion of large ships, is capable of burning very-low-grade fuels such as high-sulfur crude or heavy residual oil. Recent experiments have shown that it may even be capable of burning a powdered coal-water slurry. System costs, including heat recovery boilers, range from about $1200 to $1800 per kilowatt.

Combustion Gas Turbines. Combustion gas turbines are well suited as topping units for large-scale systems, particularly where natural gas or clean burning byproduct fuels such as refinery gas are available. Gas turbine systems offer low capital cost, about \$500–\$1000 per kilowatt, particularly in large systems of 10 to 150 megawatts. Also, the high exhaust gas temperature of gas turbines permits their integration with a great variety of industrial processes.

Spark-Ignition Engines. Spark-ignition engines that burn natural gas can also be used as topping units. A relatively new concept for achieving very low capital cost is based upon derated automobile engines converted for use in prepackaged cogeneration modules. One module generates about 30 kilowatts of electricity and about 230,000 kilojoules per hour of hot water at 110°C. Another module generates about 60 kilowatts of electricity and about 460,000 kilojoules per hour of process heat in the form of low pressure steam and hot water. Combinations of several modules can be used in applications such as shopping centers, hospitals, apartment buildings, and light industrial sites, to supply all on-site electrical and process heat needs.

Other modules are rated at 200 kilowatts, and 600 kilowatts of electricity, and proportionately higher thermal outputs, including relatively high pressure steam. For example, a natural-gas, turbocharged internal combustion engine, coupled with an electric generator and a twin-helical screw steam compressor can generate between 480 and 650 kilowatts of electricity, and between 1400 and 1700 kilograms per hour of high pressure process steam at about 10 atmospheres. Prior to the introduction of the screw compressor, cogenerators requiring high-pressure process steam were forced to use combustion turbines rather than reciprocating engines which yield much higher electrical output efficiency.

Organic Rankine Turbines. An organic Rankine turbine is an advanced type of bottoming unit. It uses an organic material as a working fluid and is capable of recovering efficiently the energy from low-temperature (150 to 600°C) waste streams. It can be built in a wide range of sizes, from as small as 50 kilowatts to 30,000 kilowatts or more. Output per unit of waste energy input will generally be 20 to 30 percent greater than that obtainable with steam-turbine bottoming units. Commercialization of organic Rankine turbines is just beginning.

The various technologies described above provide the basis for virtually all cogeneration systems. Other technologies now in the research and development stage will also play a role in future cogeneration systems.

3.

TYPICAL APPLICATIONS

Cogeneration

Cogeneration has been practiced for many decades. The advent of the energy crisis in the 1970’s rekindled the interest in cost-effective, energy-saving technologies, in general, and cogeneration in particular. A few examples of recent additions to the U.S. cogeneration capacity are as follows.

A number of units have been developed, and are owned and operated by Applied Energy Services. One of these is a \$280 million petroleum coke-fired facility in Houston, Texas, designed and constructed by Bechtel Power Corporation. Its electrical rating is 140 megawatts, and its thermal output is 15 short tons of process steam per hour. The electricity is sold to the Houston Light and Power Company, and the steam to the local ARCO refinery which also supplies the petroleum coke. The plant began commercial operations in July 1986.

Another unit is a \$116 million coal-fired plant purchased from ARCO, and refurbished by Bechtel. It is located in Monaca, Pennsylvania. It generates 121 megawatts of electricity, and 43 short tons of process steam per hour. The electricity is sold to West Penn Power, and the steam to ARCO Chemical. The plant became operational in July 1987.

A third plant is a \$120 million gas-turbine project in Newhall, California, designed and constructed by Brown Boveri Corporation. It generates about 100 megawatts of electricity sold to Southern California Edison, and 125 short tons of process steam per hour supplied to local oil leases and other steam users. It began operations in 1988.

Many smaller cogeneration plants have been designed and built by Thermo Electron Corporation.

One is a diesel cogeneration system at the Hoffmann-La Roche chemical plant in Belvidere, New Jersey. It generates 23 megawatts of electricity, and can also produce 72.6 tonnes of process steam per hour, and 119 tonnes of 76.6ºC water per hour. It supplies all the electrical and thermal needs of the chemical plant, and excess electricity is sold to the local utility. The plant began commercial operation in December 1982, and achieves the overall energy use of 87 percent. Without cogeneration, the energy consumption would have been larger by the equivalent of 200,000 barrels of oil per year.

A simple schematic of the Hoffmann-La Roche plant is shown in Figure 3. The engine is a 10-cylinder Sulzer 10 RNF 90 M, two-stroke diesel which delivers 23. 3 MW at 120 r/min. It has a 900 mm bore and 1,550 mm stroke. Overall height is 11.6 m with a baseplate of 4 m and a length of 21.51 m. Net weight is 980 tonnes. It operates on residual fuel.

The generator is manufactured by Siemens, and is a 60-pole, three phase, 13, 800 volts, 60 Hertz synchronous unit.

Waste heat from the diesel engine is recovered from the exhaust gases, air cooler, and engine water cooling circuits. In order to maximize the overall thermal efficiency, the temperature levels of the waste heat are matched to the plant thermal requirements.

The boiler is supplementary fired because the chemical plant has a requirement of up to 72.6 tonnes of 15 bar steam, much greater than the amount that can be obtained without the supplementary firing. Additional oxygen beyond that already contained in the gases is not necessary because of the large amount of excess air used in the two-stroke diesel engine.

An energy balance of the plant is shown in Figure 4.

A second example is an installation at the downtown Government Center in Dade County, Florida. This cogeneration unit began operation in December 1986. All of the electrical power, air-conditioning, and hot water needs of the Center are met by a $30 million combined-cycle cogeneration system supplied on a turnkey basis by Thermo Electron.

The Dade County Downtown Government Center is a complex of seven buildings, including a 30 storey office block, county courthouse, public library, museum, and a center for the fine arts. The cogeneration system installed meets the electricity, air conditioning, and hot water needs of the complex with an energy efficiency in excess of 76 percent when the air conditioning load is highest.

At the heart of the system are two turbine generator sets (Figure 5). The main electricity generation is provided by a Rolls-Royce SK30 industrial Olympus gas turbine with a maximum continuous site rating of 22 MWe. Normally, the turbine operates on natural gas but it is capable of burning fuel oil in emergency or abnormal conditions. The turbine exhaust is ducted to an unfired, dual pressure, natural circulation waste heat recovery boiler providing steam for a 10 MWe Peter Brotherhood dual pressure condensing turbine. High pressure steam (42 bar) is taken from one section consisting of a superheater, steam generator, and economizer. The exhaust gases then pass through a second section consisting of another steam generator and economizer producing steam at 1.4 bar. Exhaust gas leaving the boiler is ducted to a dual-wall steel exhaust stack.

The high pressure steam is fed to the steam turbine. When power demand is high, the low pressure steam is also routed to the turbine. At times of high air conditioning demand, all low pressure steam and additional low pressure steam taken from between the low pressure and high pressure sections of the steam turbine is routed to the absorption chillers, which have a combined maximum output of 18.3 MW of refrigeration.

Condensate from the chillers is pumped through a heat exchanger before being returned to the deaerator for the production of up to 1,200 litres/min of domestic hot water.

Cogeneration modules of 30 to 600 kilowatts are manufactured by Tecogen, a majority-owned subsidiary of Thermo Electron Corporation. Modules have been installed and are being operated for a great variety of uses. A sixty kilowatt unit has been installed in each of the following sites: an athletic club in Escondido, an athletic club in San Juan Creek, the Capistrano by the Sea Hospital and Clinic, and a Ramada Inn, all in Southern California. The annual savings in each of these installations are between $20,000 and $30,000, and the payback period is between two and three years. Six Tecogen modules, 60 kilowatts each, are operating on the campus of Albion college in Michigan since December 1984. They provide electricity, hot water for showers, space heating, and swimming pool heating. Also, a four Tecogen system, rated at 240 kilowatts, is installed at a 21,200 square

Table 1: Specifications of Tecogen Modules

Unit	CM30	CM60	CM200	CM600
Outputs:				
Electrical	30 kW	60 kW	200 kW	480 to 650 kW
Hot water	230 MJ/hr at 110°C	460 MJ/hr at 110°C	1,250 MJ/hr at 93°C	Amount depends on steam rate
Steam	---	---	---	1,700 kg/hr at 1 bar to 1,450 kg/hr at 8.5 bar
Input	Natural gas or propane			
Overall energy efficiency (%)	89.5	93.7	86.6	84
Controls	Completely automated. Unattended operation.			

meter building complex in North Haven, Connecticut. The system satisfies the electricity, hot water, and heating and cooling requirements of the buildings.

A 200-kilowatt gas-fueled Tecogen module is providing electricity, space heating, and hot water to a Sheraton Hotel in Danvers, Massachusetts. A duplicate unit is operating at OK Towel and Uniform Supply, a commercial laundry in Elizabeth, New Jersey. Two 500 kilowatt units have been installed by New England Electric System at a paper mill and a tool manufacturing plant, both in Massachusetts.

Configuration schematics for the 30, 60, 200, and 600 KW modules are shown in Figures 6 to 9, and technical specifications are listed in Table 1.

Wood/Biomass Fueled Systems

A number of biomass fueled electric power systems have been built by Thermo Electron. The Hemphill Power and Light project (Figure 10), in Springfield, New Hampshire, the Whitefield Power and Light project (Figure 11), in Whitefield, New Hampshire, and the Gorbell project (Figure 12), in Athens, Maine, are three wood-fueled electric power plants. Each generates 16 MW of electricity, is fueled by sawmill residue and whole tree chips, and has a cost of $\$31 \times 10^6$. The first two went into commercial operation in 1987, and the third in the summer of 1988.

Biomass fuel delivered to the plant, first passes over a weighing station and then is dumped onto the processing line. Conveyors transport the fuel to a processing facility for size separation. Fuel that is two inches or under, in all dimensions, passes through a rotating disc screen. Fuel over two inches passes to a swing hammermill for size reduction down to two inches. Fuel can then be conveyed to the boiler feed bin or moved to storage, which can be open pile, covered pile or silo.

The boiler fuel feed system incorporates live bottom surge hoppers to maintain the fuel inventory needed for operational flexibility. The steam generator is a bottom-supported, field erected, water cooled vibrating grate and balanced draft boiler. Hot gases generated in the furnace pass through the superheater, boiler bank, economizer and air heater sections before entering the flue gas cleaning system which typically consists of cyclone collectors followed by an electrostatic precipitator.

Power is generated by a single inlet, extraction/condensing steam turbine connected to a generator. The operation of the fuel processing, steam generating unit, air equipment, plus the cooling tower and electrical transmission, is controlled and monitored from a central control room.

Three agricultural waste power plants are being built in California. The Mendota Biomass Power, Ltd., in Mendota (Figure 13) is a 28 MW electric power plant using a circulating fluidized bed boiler, and fueled by woodwaste and prunings from orchards and vineyards. Its cost is $\$70\times10^6$. It went into commercial operation in the summer of 1989. It sells its electricity to Pacific Gas and Electric.

The Woodland Biomass Power, Ltd. , in Woodland is a 28 MW electric power plant using a circulating fluidized bed boiler, and fueled by rice hulls, rice straw, orchard prunings, and woodwaste. Its cost is $\$80\text{x}10^6$, and it is scheduled for commercial operation in late 1989. It will sell its electricity to Pacific Gas and Electric.

The Delano Energy Company, Inc., in Kern County is a 30 MW electric power plant using also a circulatory fluidized bed boiler, and fueled by wood and agricultural wastes. Its cost is $\$85\text{x}10^6$, and it is scheduled for operation in mid-1990. It will sell its electricity to Southern California Edison Company.

The fluidized bed boilers in the three California plants are used with special flue gas treatment such as thermal de-NOx and/or baghouse to comply with the very strict environmental regulations of the State of California.

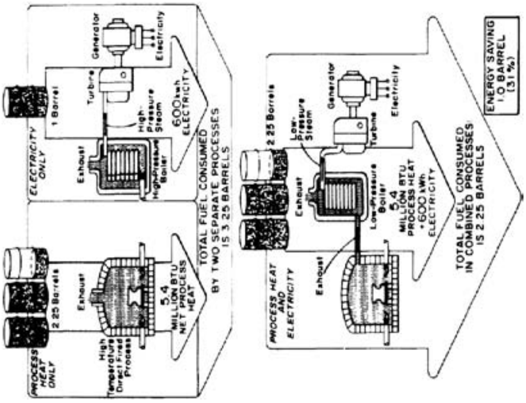


Fig.1

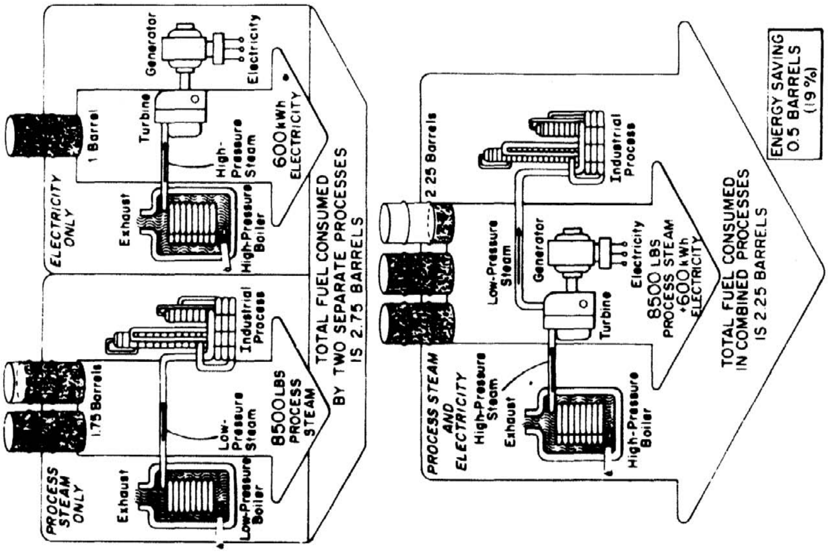

PROCESS STEAM ONLY
Exhaust
Low-Pressure Boiler
1.75 Barrels
Low-Pressure Steam
Industrial Process
8500 LBS PROCESS STEAM
ELECTRICITY ONLY
Exhaust
High-Pressure Boiler
1 Barrel
High-Pressure Steam
Turbine
Generator
Electricity
600 kWh ELECTRICITY
TOTAL FUEL CONSUMED BY TWO SEPARATE PROCESSES IS 2.75 BARRELS
PROCESS STEAM AND ELECTRICITY
High-Pressure Steam
Exhaust
High-Pressure Boiler
2.25 Barrels
Low-Pressure Steam
Generator
Turbine
Electricity
Industrial Process
8500 LBS PROCESS STEAM +600 kWh ELECTRICITY
TOTAL FUEL CONSUMED IN COMBINED PROCESSES IS 2.25 BARRELS
ENERGY SAVING 0.5 BARRELS (19%)

Fig.2

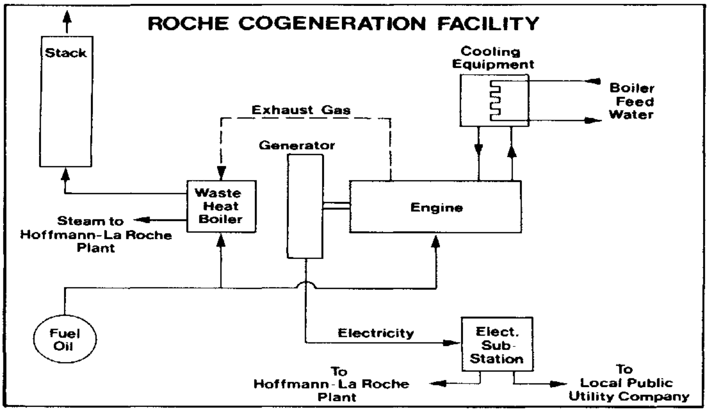
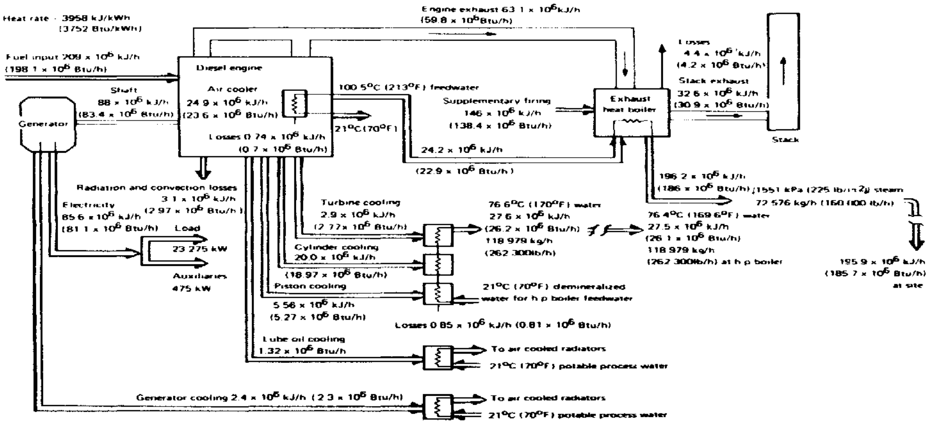

ROCHE COGENERATION FACILITY
Stack
Cooling Equipment
Boiler Feed Water
Exhaust Gas
Generator
Waste Heat Boiler
Engine
Steam to Hoffmann-La Roche Plant
Fuel Oil
Electricity
Elect. Sub-Station
To Hoffmann-La Roche Plant
To Local Public Utility Company

Fig.3



Cogeneration system energy balance (23.3 MW, ambient air at 20°C, 68°F)

Fig.4

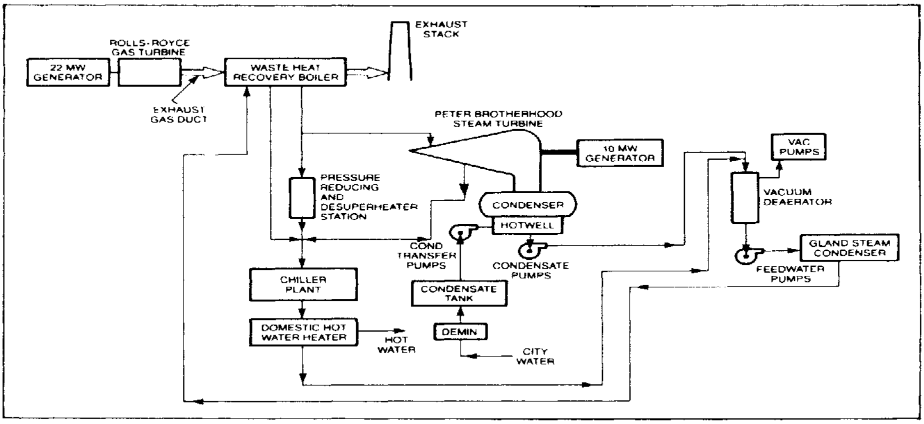


Fig.5

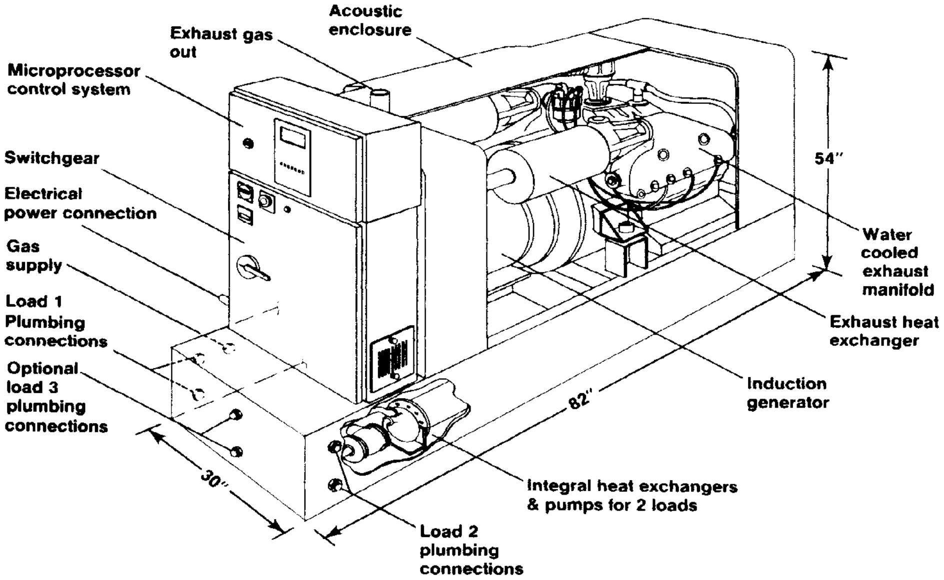

Acoustic enclosure
Exhaust gas out
Microprocessor control system
Switchgear
Electrical power connection
Gas supply
Load 1 Plumbing connections
Optional load 3 plumbing connections
30"
82"
54"
Water cooled exhaust manifold
Exhaust heat exchanger
Induction generator
Integral heat exchangers & pumps for 2 loads
Load 2 plumbing connections

Fig.6

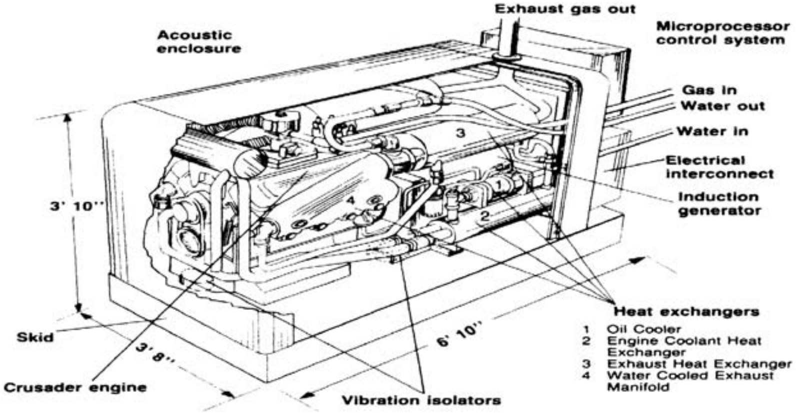

Exhaust gas out
Acoustic enclosure
Microprocessor control system
Gas in
Water out
Water in
Electrical interconnect
Induction generator
3' 10"
3
1
2
4
Heat exchangers
1 Oil Cooler
2 Engine Coolant Heat Exchanger
3 Exhaust Heat Exchanger
4 Water Cooled Exhaust Manifold
Skid
3' 8"
6' 10"
Crusader engine
Vibration isolators

Fig.7

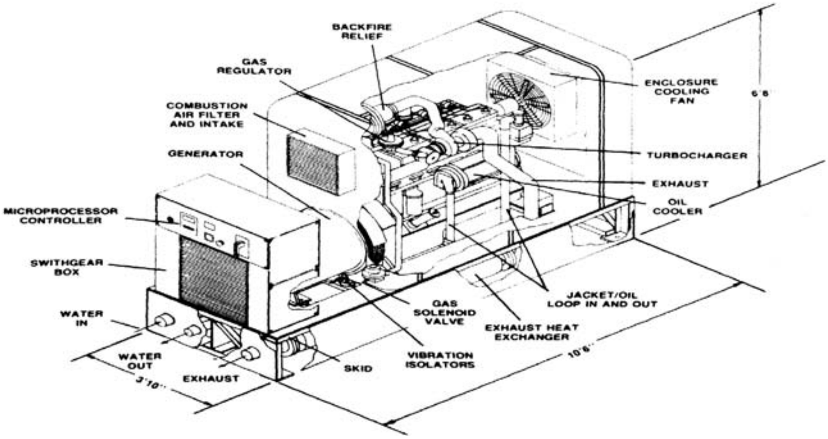

BACKFIRE RELIEF
GAS REGULATOR
COMBUSTION AIR FILTER AND INTAKE
GENERATOR
MICROPROCESSOR CONTROLLER
SWITHGEAR BOX
WATER IN
WATER OUT
EXHAUST
3'10''
SKID
VIBRATION ISOLATORS
GAS SOLENOID VALVE
EXHAUST HEAT EXCHANGER
10'6''
JACKET/OIL LOOP IN AND OUT
OIL COOLER
EXHAUST
TURBOCHARGER
ENCLOSURE COOLING FAN
6'8

Fig.8

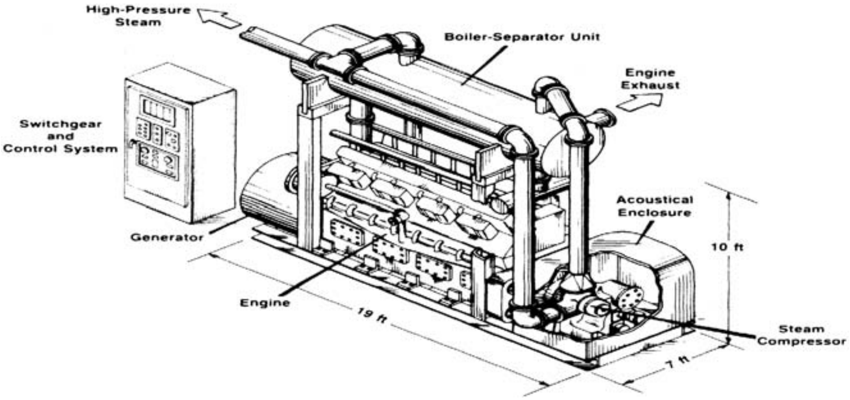

High-Pressure Steam
Boiler-Separator Unit
Engine Exhaust
Switchgear and Control System
Acoustical Enclosure
10 ft
Generator
Engine
19 ft
7 ft
Steam Compressor

Fig.9

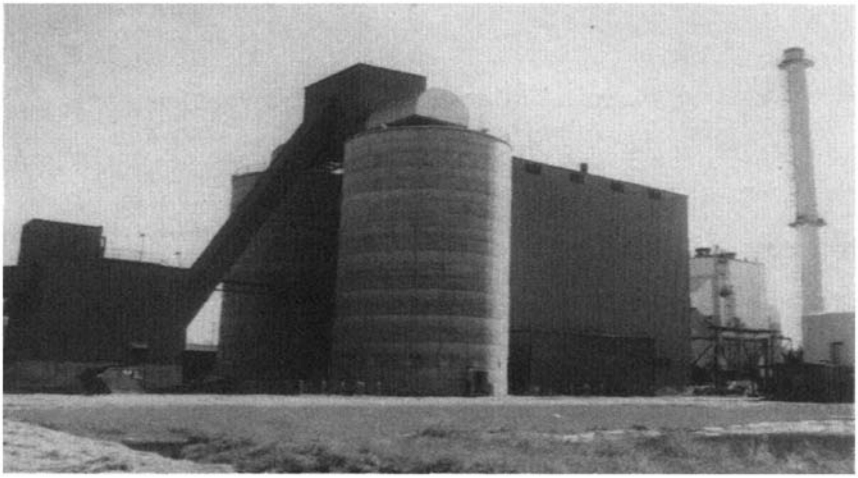


Fig.10

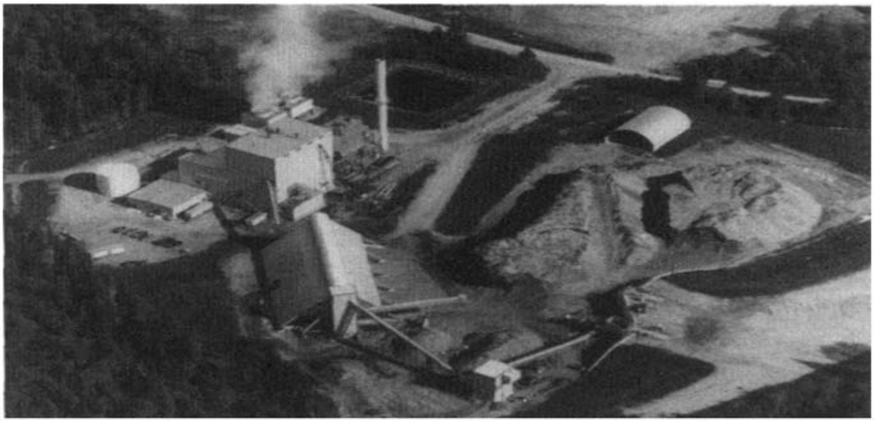


Fig.11

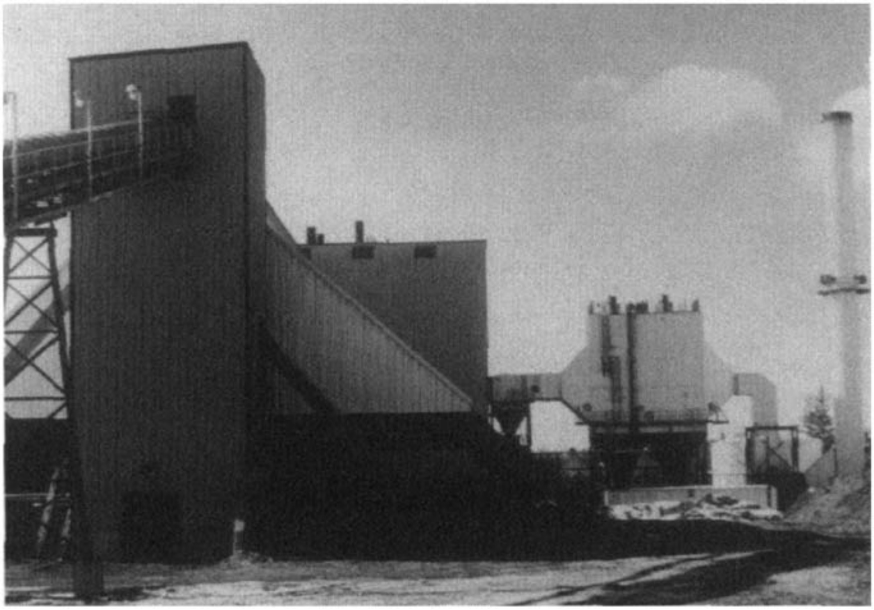


Fig.12

MENDOTA BIOMASS POWER, LTD.

Fig.13

COMBINED PRODUCTION OF HEAT AND POWER (COGENERATION)

Edited by

J.SIRCHIS
*Directorate-General for Energy, Commission of
the European Communities,
Brussels, Belgium*

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