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COGENERATION - INTERACTIONS OF GAS TURBINE, BOILER AND STEAM TURBINE

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ABSTRACT

A gas turbine cogeneration plant produces power and process steam. Under the PURPA law, surplus electric power can be sold to the local utility. Since process steam generally cannot be exported, it is better to have an excess of power than an excess of steam.

Because of low rates offered for surplus power, or for other possible reasons, an owner may not wish to sell power, so it may be necessary to operate at a power-to-steam ratio that does not match the outputs of a gas turbine with a simple heat recovery boiler. If more steam is needed, supplementary firing may be included in the heat recovery boiler.

If the need is for more power, a back pressure steam turbine can be included. This reduces the steam output by requiring higher steam pressure. Further power increase and steam reduction can be obtained with a condensing steam turbine. If neither the full steam output nor additional power is required, capital cost can be reduced by inclusion of a smaller, less-efficient heat recovery boiler.

This paper compares these means of adjusting the power and steam outputs of a gas turbine cogeneration system to obtain the most cost effective system.

INTRODUCTION

Cogeneration is the sequential production of power and process heat from a single fuel by using some of the heat that is left over from power generation. When credited with the useful recovered heat, cogeneration is more efficient than separate power and heat generation.

This paper discusses cogeneration plants consisting of a gas turbine, a heat recovery boiler, and a steam turbine. Performance, capital cost and return on investment are estimated on a simple basis.

The gas turbine is a 40 MW Westinghouse Canada CW251B, using natural gas. Systems with back pressure and condensing steam turbines, or with no steam turbine, are considered. Typical systems are depicted on Figures 1, 2 and 3.

Revenue is calculated at the avoided cost of power and process steam. Expenses include fuel, operators, and maintenance. The systems are compared on the basis of simple internal rate of return, and net annual revenue (before taxes) divided by capital cost. The trends of power, capital cost, and simple return are shown on Figure 4.

Capital costs are derived from algorithms that include all costs involved in placing the equipment in service, including a proportion of control room and personnel facilities.

SYSTEM COMPONENTS

GAS TURBINE

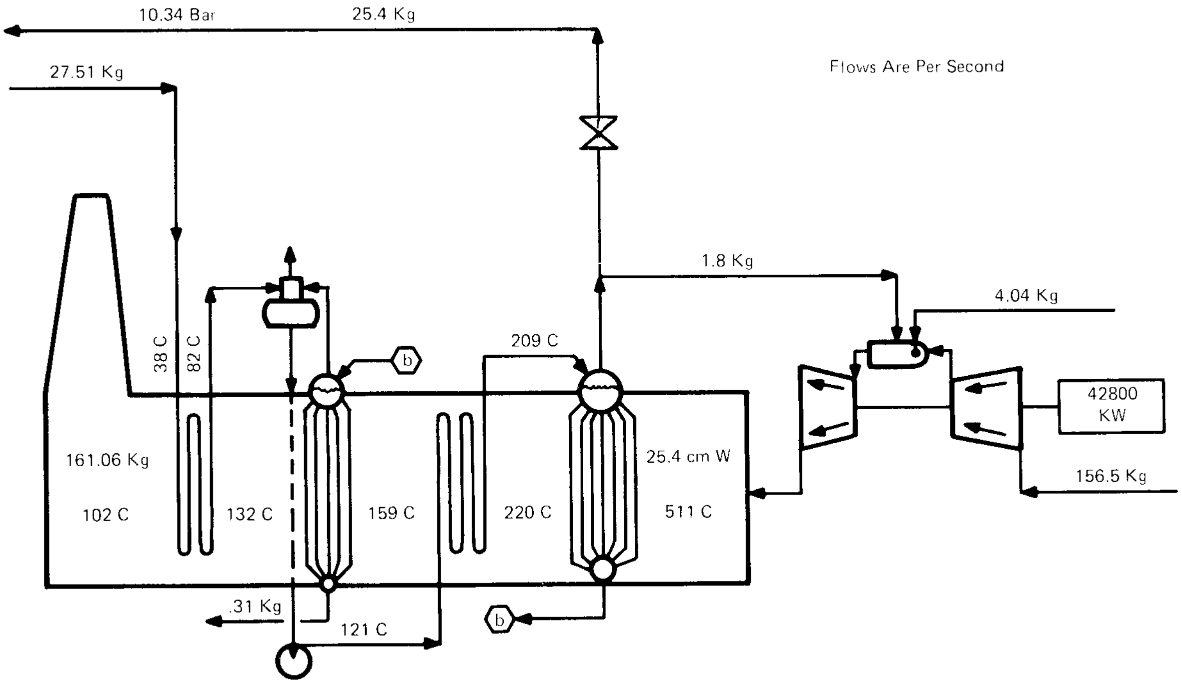
The gas turbine in the study is a Westinghouse CW251B, which has a 42,000 kW ISO continuous rating. Introduced in 1967, this model has accumulated more than one million operating hours.

The CW251 is a single-shaft, heavy-duty, two-bearing machine with horizontally split casings. The turbine runs at 5400 rpm and drives the generator through a reduction gear. The reduction gear ratio and the generator speed can be varied to accommodate 50 or 60 cycle power.

The 14 pressure ratio compressor has 19 stages and the expander has three. Eight internal combustors are close coupled to the expander. First stage expander cooling air is cooled before use, and fuel for the gas turbine and for supplementary boiler firing is natural gas. Steam is injected to suppress NO_x or for augmenting power.

Inlet pressure drops of silencing and filtration is 10 cm (4 in) water; optimum pressure drops through the heat recovery boilers, which adequately silence the exhaust, fall between 36 cm (14 in) and 83 cm (33 in) of water. With steam injection, exhaust flow is 161 kg (355 lb) per second at 511°C (951°F) and power output is 42,800 kW with 36 cm water back pressure.

Gas turbine generator costs include foundations, intake system, circuit breakers, lubrication, cooling, controls, maintenance crane and building. The exhaust system is excluded, since it is replaced by the heat recovery boiler.



Flows Are Per Second

Figure 1. Gas Turbine and Unfired Process Steam Boiler

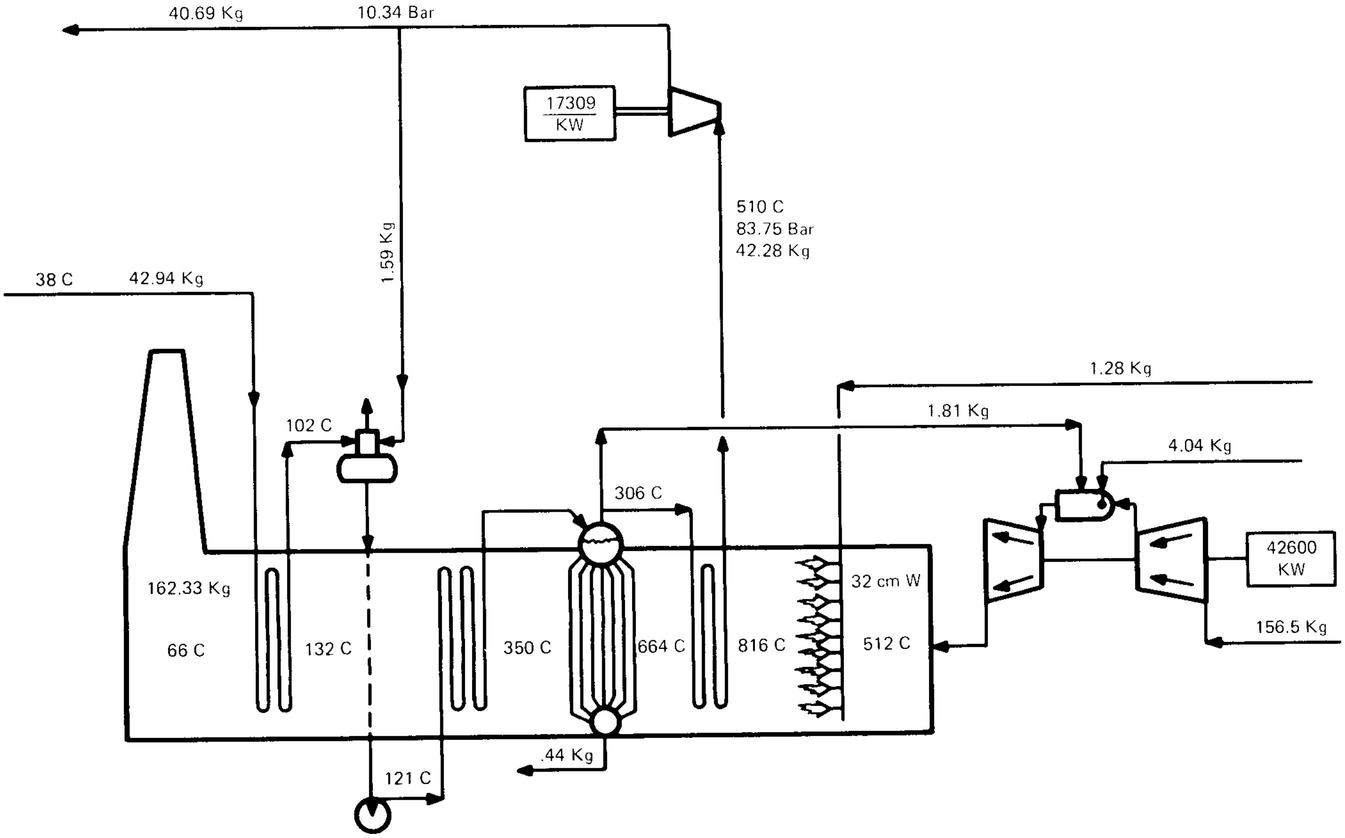


Figure 2. Gas Turbine Fired Boiler Back Pressure Steam Turbine

HEAT RECOVERY BOILER

All the heat recovery boilers in the study include a main evaporator and economizer, a feed pump system, and a deaerator, and have a 15 meter (50 ft) stack and other normal apurtenances.

Other components, added as required, include the superheater, intermediate pressure evaporator and economizer, low pressure evaporator to supply the deaerator, supplementary firing system, and a low temperature economizer.

The low temperature economizer is included when the heat available to the deaerator is inadequate to preheat the incoming water to 250°F from 100°F. The low temperature economizer, made of corrosion resistant material, will operate below the dewpoint with underaerated water. The process steam is evaporated at 16.87 bar (230 psig) and is at a sufficiently high pressure to be injected into the gas turbine. Gas pressure drop is 36 cm (14 in) of water in the unfired boilers and up to 83 cm (33 in) in the fired boilers, depending on their complexity.

With a steam turbine, an intermediate injection and process steam evaporator may be included in the boiler.

The diagrams in Figures 1, 2 and 3 depict natural circulation boilers. The boiler costs are applicable to both natural and forced circulation, since these costs are largely established by the market place. Boiler costs include foundations, structural steel, ladders and platforms, gas enclosure (including connection to the gas turbine), insulation, heat transfer surface, pressure parts, firing system and controls (if required), stop valves, safeties, blow-down and drain valves, level and steam temperature controls, deaerator, and feed and circulating pumps (if required).

SUPPLEMENTARY FIRING

Steam production can be increased by supplementary firing of the boiler, which burns fuel with oxygen present in the gas turbine exhaust. Losses are confined to the sensible heat in the burned fuel, and efficiency of fuel utilization is about five points higher than a conventional boiler.

Supplementary firing is accomplished by a multiple fuel-jet grid burner with flame holders arranged in a lattice pattern to provide uniform temperature over the duct area.

The exhaust gas temperature can be raised to about 816°C (1500°F) with little or no change in construction of the boiler (higher temperatures require water-cooled or refractory-lined gas enclosures). Maximum gas temperature can be limited with increased supplementary firing by locating the firing system downstream of some of the heat transfer surface so that firing occurs from a lower temperature.

BOILER GAS PRESSURE DROP

Higher boiler gas pressure drop causes increased back pressure and reduced power from the gas turbine. The power loss is somewhat offset by hotter exhaust temperature and increased steam production or less supplementary fuel in the boiler.

An increase in boiler gas pressure drop will permit less boiler face area, tighter tube spacing, or more finning, and will reduce boiler cost.

The heat transfer surface area in a boiler is a function of the boiler duty and an inverse function of the weighted average of the Mean Temperature Differences (MTD) of the sections.

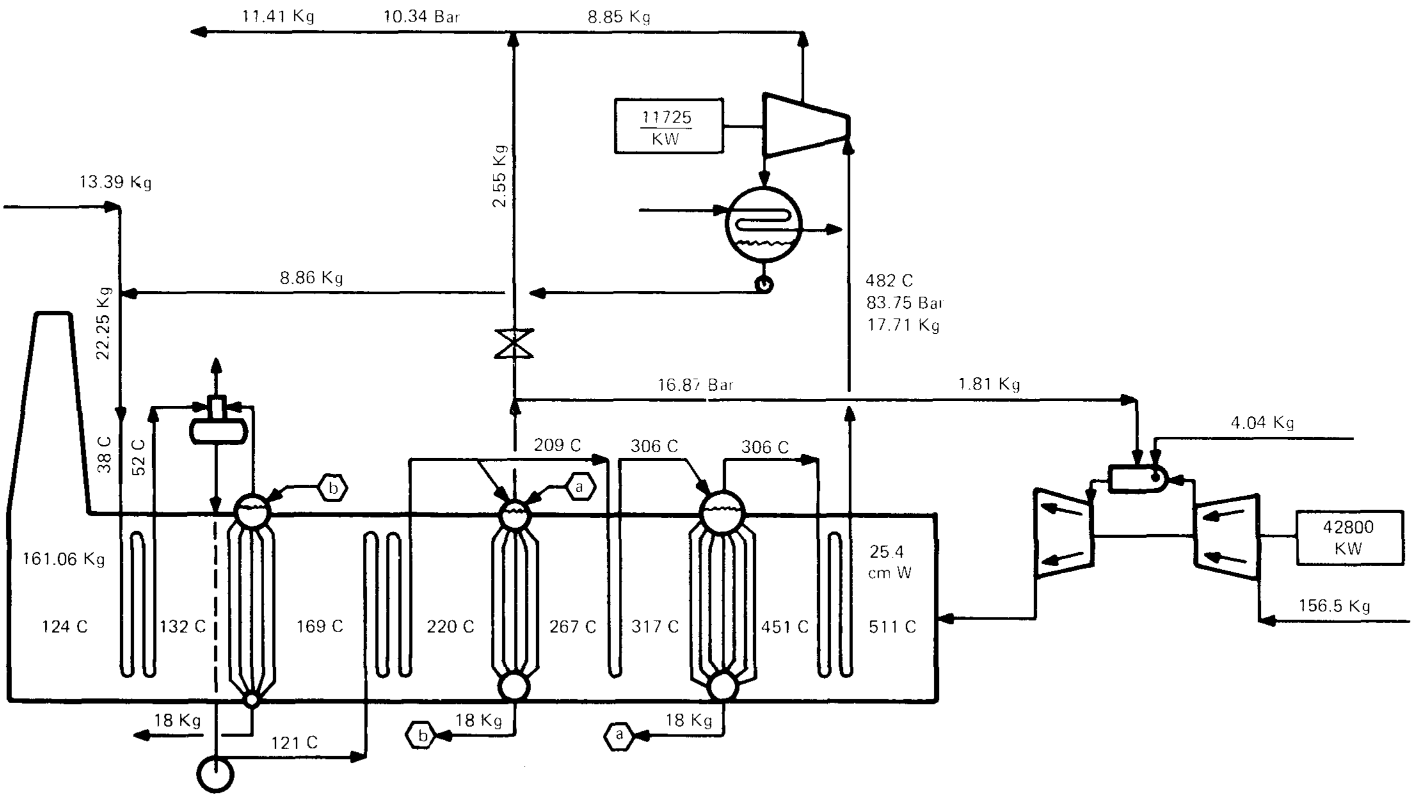


Figure 3. Gas Turbine, Unfired Boiler, Extraction Condensing Steam Turbine

For equal approach temperatures the average MTD is a minimum when the heat capacities (flow rate x specific heat) of gas and water are equal. This occurs when gas and water flows are in inverse relationship to their specific heats (when gas flow ~ 4 x water flow). This condition is attained with supplementary firing. When the heat capacities of gas and water are about equal, average MTD is at a minimum and the boilers require a lot of surface and are costly. This condition occurs at steam flows of 35-40 kg/sec with the CW251 engine. The cost of the boiler is reduced if the gas pressure drop is increased.

With the more expensive boilers, the cost saving from higher gas pressure drop exceeds the penalty from higher back pressure, which makes it cost effective to increase the gas pressure drop to enhance heat transfer, reduce area, and reduce cost when a boiler requires a lot of surface (as when the gas and water heat capacities are about equal).

In a system without a steam turbine, when power is more valuable than steam, it can be cost effective to reduce the cost of expensive boilers by widening the temperature approach while retaining the low gas pressure drop.

For steam output in excess of the heat capacity balance quantity, approximately 45 kg/sec, the MTD widens such that the boiler cost does not further increase with more firing.

In the case of the higher pressure boiler with the steam turbine, the boiler becomes more simple with increased firing and the boiler cost is reduced. The complication required in the unfired high pressure boiler (to circumvent the heavy temperature pinch) relative to the fired HP boiler can be observed by comparison of Figures 2 and 3.

The impact of equal gas and water heat capacities on system cost and return can be seen on Figure 4 as an inflection in the trends.

STEAM TURBINES

The steam turbines are direct-connected to air cooled electric generators and operate at 3600 rpm for 60 cycle power, and 3000 rpm for 50 cycle power.

Back pressure and extraction condensing steam turbines are both considered. Exhaust or extraction for process is at 11.36 bar abs (150 psig) and condenser pressure is 7.62 cm (3 in) of mercury.

Throttle pressure is 83.75 bar abs (1200 psig). With unfired boilers, steam temperature is 482°C (900°F) and with supplementary firing steam is 510°C (950°F).

Steam turbine generator costs include foundations, isolation and control valves and system, circuit breakers, lubrication system, a portion of the maintenance crane and building, and the condenser when applicable.

COST EFFECTIVENESS ANALYSIS

For easy application of the results, this economic analysis is simplified. Economic merit is expressed as the annual net return before taxes as a percentage of the capital cost. A conversion to discounted return for 100 percent equity financing can be made by using Figure 5 (leveraged financing increases the returns).

Net return consists of revenues from electric power and from process steam, less cost of fuel, operators and maintenance. The plant is assumed to operate for the equivalent of 7000 full capacity hours per year.

Electric power is credited at 6 cents per kWhr and process steam at $15.43 per metric ton ($7 per thousand pounds). Natural gas is charged at $5.27 per million net kilojoules ($5 per million Btu HHV).

Operators are charged at $100,000 per shift position per year; a gas turbine and heat recovery boiler require two positions and a combined cycle requires three positions. Maintenance is included at two percent of the capital cost per year.

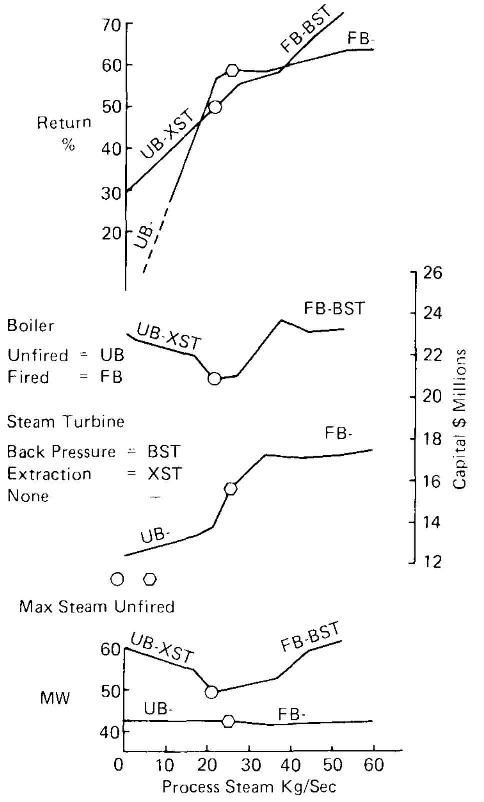


Figure 4. Parametric Performance

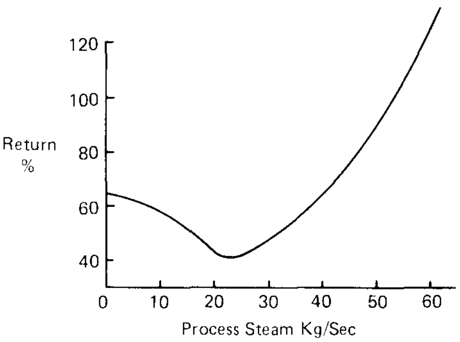


Figure 5. Incremental Return on the Cost of a Combined Cycle in Excess of the Cost of a Gas Turbine and Boiler

SYSTEMS PERFORMANCE

GAS TURBINE WITH HEAT RECOVERY BOILER

The most simple system consists of the gas turbine and an unfired heat recovery boiler producing 25.4 kg/s (57 lb/sec) of saturated steam for process (Figure 1).

The exhaust gas is cooled to a stack temperature of 102°C (216°F). The return on the investment before taxes with this simple system is 59 percent. If less steam is required, a lower cost boiler with less surface area can be purchased resulting in more heat loss up the stack.

The initial 14 percent reduction in steam output produces a significant capital saving of about $1.7 million and return is reduced to only 56 percent. Further reductions in boiler surface effect only small capital savings and significant loss of return on investment. A 50 percent reduction in steam reduces return to 30 percent.

These trends are shown on Figure 4, where the gas turbine with unfired boiler and no steam turbine is designated UB-. The cases with unfired boilers and maximum steam production are circled.

Steam production is extended from 25.4 to 60 kg/sec by supplementary firing. Firing increases the mean temperature difference in a boiler; after the initial increment of the firing system, cost is not increased by additional firing.

The initial increase in cost and fuel use due to boiler firing is offset by the increased steam output, and return is almost unchanged at 58.5 percent. Further firing increases output at no increase in cost, and return is increased to 63 percent.

Supplementary firing represents an additional highly-profitable investment provided that adequate credit can be obtained for the additional steam.

GAS TURBINE WITH BOILER AND STEAM TURBINE

Expanding the process steam through a steam turbine generates additional high-efficiency power. Capital cost is increased by the more complicated higher pressure boiler and by the steam turbine.

With a steam turbine, steam pressure is increased to 83.75 bar abs (1200 psig). With unfired boiler, steam temperature is 482°C (900°F); with supplementary firing, it is 510°C (950°F).

With an unfired boiler and back pressure steam turbine, total power is 49 MW with 21.5 kg/sec steam to process. Return on investment is 50 percent, as indicated by the circled point on the XST - BST lines on Figure 4.

Supplementary firing up to the equal water and gas heat capacities reduces the boiler mean temperature difference and increases cost. More firing simplifies the boiler, widens the MTD, and reduces boiler cost. Supplementary firing increases the return on investment to 72 percent at 52.5 kg/s of steam and 61.5 MW of power.

As with the simple gas turbine/HRB, supplementary firing is cost effective if a use exists for the increased steam at an adequate credit. The quantity of process steam can be reduced by condensing a portion of the produced steam in an extraction condensing steam turbine (XST on Figure 4).

The unfired boiler with back pressure steam turbine sending all 21.5 kg/sec of steam to process generates 49.5 MW, costs $21 million, and returns 50 percent. The same system, condensing all the steam and sending no steam to process, generates 60 MW, costs $23 million, and returns 30 percent. Intermediate conditions produce proportional returns.

DISCUSSION

The combination of a gas turbine with a heat recovery boiler produces power and steam at high efficiency and lower capital cost than a combined cycle system. This simple system, without a steam turbine, is often the most cost effective arrangement.

The Public Utilities Regulatory Policies Act (PURPA) allows surplus cogenerated electric power to be sold, generally at a profit. Since steam usually cannot be exported, credit may not be obtained for steam not used on site. However, steam that cannot be used for process on site can be used in a steam turbine to generate additional power that can be exported for revenue.

If steam that could be produced exceeds site requirements, it is generally cost effective to use a back pressure or extraction turbine, which requires that the steam pressure be raised. This reduces the quantity of steam produced by the exhaust heat.

The steam turbine and the higher pressure boiler require additional investment, but the additional power provides the return.

When all the steam produced by the exhaust of the gas turbine cannot be used or exported, capital can be conserved by installing a boiler with reduced surface. An alternative is installation of a full capacity boiler with a stack to vent gas turbine exhaust in excess of the flow required to produce the steam. The bypass stack requires dampers and a silencer, and the exhaust passing through a boiler is effectively silenced.

With a bypass stack, full boiler output can be obtained for future plant expansions or to cover outage of other equipment by closing the bypass damper and directing all exhaust through the boiler. This is not possible if a reduced surface area boiler is used.

A compromise can be the cost effective solution. An 80 percent capacity boiler (which costs 40 percent less than a full capacity boiler), for example, may be combined with a bypass stack. Including the bypass, the cost of the boiler system is reduced by 30 percent.

The inclusion of a steam turbine to use excess steam capacity from a full capacity boiler is more costly than the lower capacity boiler with bypass stack. Revenue is increased by sale or credit for power produced in the steam turbine using the excess steam.

With an unfired boiler, return on investment is increased by a steam turbine (UB-XST) if steam requirement for process is less than 70 percent of the output of unfired process steam boiler (UB- on Figure 4).

Without a steam turbine, when output of steam is increased by supplementary firing, only steam output is increased. With a steam turbine, both steam and power are increased by supplementary firing.

If the output of process steam is to be increased more than 46 percent above the output of the unfired process boiler, return on investment will be increased by including a back pressure steam turbine (Figure 4, FB-BST and FB-). Except for process steam flows between 18 and 38 kg/s, the combined gas turbine/steam turbine system is more profitable than the simple system without a steam turbine.

Condensing 1000 lb of process steam will generate 72 kW/hr (worth $4.32). The same 1000 lb of process steam is worth $7.00 as process steam. Raising 1000 lb of steam by supplementary firing requires incremental natural gas, costing between $4.70 and $6.50, depending on the degree of firing. Condensing steam raised by supplementary firing ordinarily is a losing proposition, but condensing steam from an unfired boiler may be cost effective.

A decision whether to install a combined cycle system rather than the less costly gas turbine boiler system should be based on the return on the incremental investment.

The return on the additional capital cost of a combined cycle versus the process steam ouput is shown on Figure 5. The minimum simple incremental return is 40 percent, equivalent to a discounted rate of return -- as defined on Figure 6 -- of 30 percent.

A combined cycle appears to be the most cost effective option, with simple return exceeding a hurdle rate of 40 percent, for all the process steam flows above 12 kg/sec.

Equity	100%
Depreciation	5 Years
Economic Life	10 Years
Investment Tax Credit	10%
Escalation	6%
Income Tax	50%

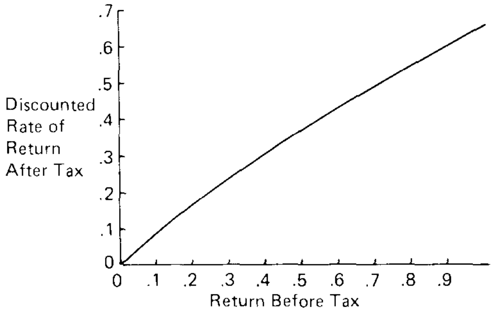


Figure 6. Simple Rate of Return Before Taxes, and Discounted Return After Taxes

CONCLUSION

By varying the capacity of the heat recovery boiler, by omitting (or including) supplementary firing, and by omitting (or including) a steam turbine (either back pressure or condensing), it is possible to match a particular gas turbine frame to a wide range of cogeneration requirements.

When steam requirements vary significantly, a fired boiler/steam turbine combination provides greater operational flexibility. The addition of a steam turbine to the gas turbine and boiler -- to make a cogenerating combined cycle -- is a highly profitable incremental investment. The combined cycle is more profitable than a simple gas turbine and boiler over most of the range of steam outputs.

CONVERSION CONSTANTS

1 inch = 2.54 cm

1 meter = 3.281 ft

1 kg = 2.205 lb

1 °F = 1.8 °C + 32

1 bar = 14.504 psia

1 Btu = 1.0551 kJ