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INDUSTRIAL ENGINEERING PROBLEMS

(CREATIVE COMPONENT)

HEAT RECOVERY STEAM GENERATORS FOR ENERGY CONSERVATION

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HRSGs AT THE KERN RIVER COGENERATION COMPANY, KERN COUNTY, CALIFORNIA [22]

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ABSTRACT

Energy engineers and consultants involved in cogeneration feasibility studies often come across the problem of determining the gas and steam-water temperature profile and the steam generation potential in the Heat Recovery Steam Generator (HRSG).

Two important variables that effect the temperature profile and steam flow are the Pinch Point (PP) and the Approach Point (AP). Although the final selection of these parameters is determined by the size and cost of the HRSG, their effect on steam flow and temperature profile must often be evaluated in early engineering stages.

Analysis of HRSG is no doubt a tedious and time consuming task. The routine "HGPRO" developed in this report presents a simplified approach to determine the steam flow, duties of various heat transfer surfaces, and temperature profile in an unfired HRSG. The user can acquire all the required information on the performance of the HRSG without actually doing the mechanical design. Also, the additional power generation potential from the steam generated in the HRSG can be estimated using the routine.

CHAPTER 1 - INTRODUCTION

Growing energy demand coupled with limited primary energy reserves dictates a more economic and efficient use of energy and has necessiated the system designer to select a process or a system with maximum heat recovery. The subject of heat recovery, though not new, is talked all over the world today, and almost in every sphere of activity.

A waste heat recovery system can be broadly defined as any system which recovers the heat which is otherwise wasted. The waste heat recovery system can be designed to meet the process steam requirement in which case, the system consists of a Heat Recovery Steam Generator (HRSG) with associated auxiliaries. When there is no requirement for process steam, the waste heat recovery system can be designed as a power plant consisting of a HRSG, a steam turbine with an alternator, and the associated auxiliaries. When the steam generated in the HRSG is substantially more than the process steam requirement, or when the process steam is required at low pressures, the steam generated in the HRSG can be used for meeting both the process steam requirements and in the generation of additional electrical power. Usually a steam turbine with single or multi-stage extraction is used down-stream of the waste heat recovery system to accomplish the above said purpose.

Bruce et.al.[1] has reported the gas turbine orders for the period June 1989 through May 1991 in terms of the total engine output as 50,488,880 kW_e. The combined Diesel, dualfuel and gas engine orders for the same period has been reported to be 7,946,447 kW_e. Thus, it can be seen that the gas turbine orders, in terms of engine output is more than six times than other internal combustion engines. Also, gas turbine installations have a greater amount of flexibility for heat recovery when compared with other internal combustion engines. Hence, the pressing need is to develop more reliable, efficient, and economical gas turbine heat recovery systems. With this in mind, the current work focuses on gas turbine heat recovery systems only. However, the same concept and methodology can be easily extended for the design and evaluation of other internal combustion heat recovery systems.

The design of a Heat Recovery Steam Generator behind a gas turbine is based on various parameters. Unlike the parameters for the design of a conventional boiler, the input for the HRSG is neither constant nor well defined. However, with the simplified approach presented in this report, the designer can acquire information on the steam generation capacity of the HRSG without actually doing the mechanical design which means that there is no need to size the tube or fin configuration.

The routine HGPRO developed in this report can be used as a preliminary tool for obtaining all the required information pertaining to a gas turbine exhaust heat recovery system. The information that can be obtained include quantity of steam generated and gas/steam temperature across all the heat transfer surfaces in the heat recovery equipment. The output from the routine can be used in the preparation of HRSG specification sheets for obtaining budgetary estimates on the cost of the project. This information can be used with any conventional economic analysis for establishing the viability of the project.

In the hands of any energy professional, HGPRO will be an indispensable tool for the initial analysis of gas turbine heat recovery systems for existing gas turbines and in choosing the most appropriate gas turbine rating and a matching exhaust heat recovery system for any new project.

CHAPTER 2 - WASTE HEAT RECOVERY SYSTEMS
- Concepts, Technology, and Application

2.0 WASTE HEAT RECOVERY SYSTEM

A Waste Heat Recovery System (WHRS) can be broadly defined as any system which recovers the heat which is otherwise wasted. In industry, Waste Heat Boilers are commonly known as Heat Recovery Steam Generators (HRSGs). The WHRS can be designed either to supply process heat requirement usually in the form of steam or can be designed as a power plant consisting of an HRSG and steam turbine to produce electrical power. In either case, the HRSG, which recovers the waste heat to generate steam at the required parameters, is the heart of the heat recovery system and needs careful design.

2.1 WASTE HEAT POTENTIAL

Many industries exhaust flue gases at fairly high temperatures and these are tabulated in Table 2.1.

A typical 20 MW gas turbine, working on open cycle, exhausts about 238 lb/sec of flue gas at 955 °F. By installing an unfired HRSG at the down stream of the gas turbine, 48 tons/hr of superheated steam at 350 lb/psia and 760 °F can be generated by the waste heat recovery system, to ultimately produce about 10 MW of electrical power by the steam turbine. The above fact clearly indicates the enormous potential that is available for waste heat recovery in gas turbine installations. Figure 2.1 can be used to find the additional electrical power output from the unfired waste heat recovery system when fitted to any existing or new open cycle gas turbine installation.

TABLE 2.1 WASTE HEAT POTENTIAL [9]

WASTE HEAT SOURCE	SOURCE TEMPERATURE (°F)
Gas Turbine exhaust	750 - 1050
Diesel Engine exhaust	750 - 850
Flue gas form cement kilns (dry process)	650 - 700
Reformed gas, Synthesis gas and Converted gas in fertilizer plants	1650 - 2000
Flue gas in glass industries	1650 - 1850
Flue gas from various furnaces in steel industries	750 - 1650

In a typical 3,000 tons per day cement plant, 243 lb/sec of flue gases are available at approximately 700 °F from the rotary kiln. A waste heat recovery system based power plant can be suitably designed to recover heat from the above waste gases to generate 28 Tons/hr of steam at 185 psia and 580 °F which can ultimately produce about 4.2 MW of electrical power in a steam turbine. Figure 2.2 can be used to find out the possible steam generation and electrical power output from the waste heat recovery system when installed in any cement plant.

Diesel engine based heat recovery systems yield only low pressure steam and such steam can be used only for process requirements. Figure 2.3 can be used to find the possible steam generation from the diesel engine exhaust heat recovery.

Thus, charts similar to figures 2.1 to 2.3 can be developed for any installation, once the flus gas quantity and temperature are known for various capacities and operating points.

2.2 CLASSIFICATION OF WASTE HEAT BOILERS

Waste heat boilers can be broadly classified in to the following two categories.

Category I. Those boilers that are essential from the process point of view.

Category II. Those boilers that are optional from the heat recovery point of view.

2.2.1 Waste Heat Boilers of I Category

In processes like manufacture of sulphuric acid, hydrochloric acid and fertilizers, the gaseous products like reformed gas, synthesis gas, converted gas, etc., have to be cooled down to a particular temperature for a favorable reaction to occur. Cooling any gas by generation of steam is the most economical and simple method and hence, these process gases are cooled in a waste heat boiler. The steam generated by the waste heat boiler is normally utilized either for process use or for power generation in a cogeneration system. These boilers which are installed form the process point of view are more commonly called as "Process Heat Recovery Boilers".

Figure 2.4 shows the location of WHBs in a typical fertilizer manufacturing plant.

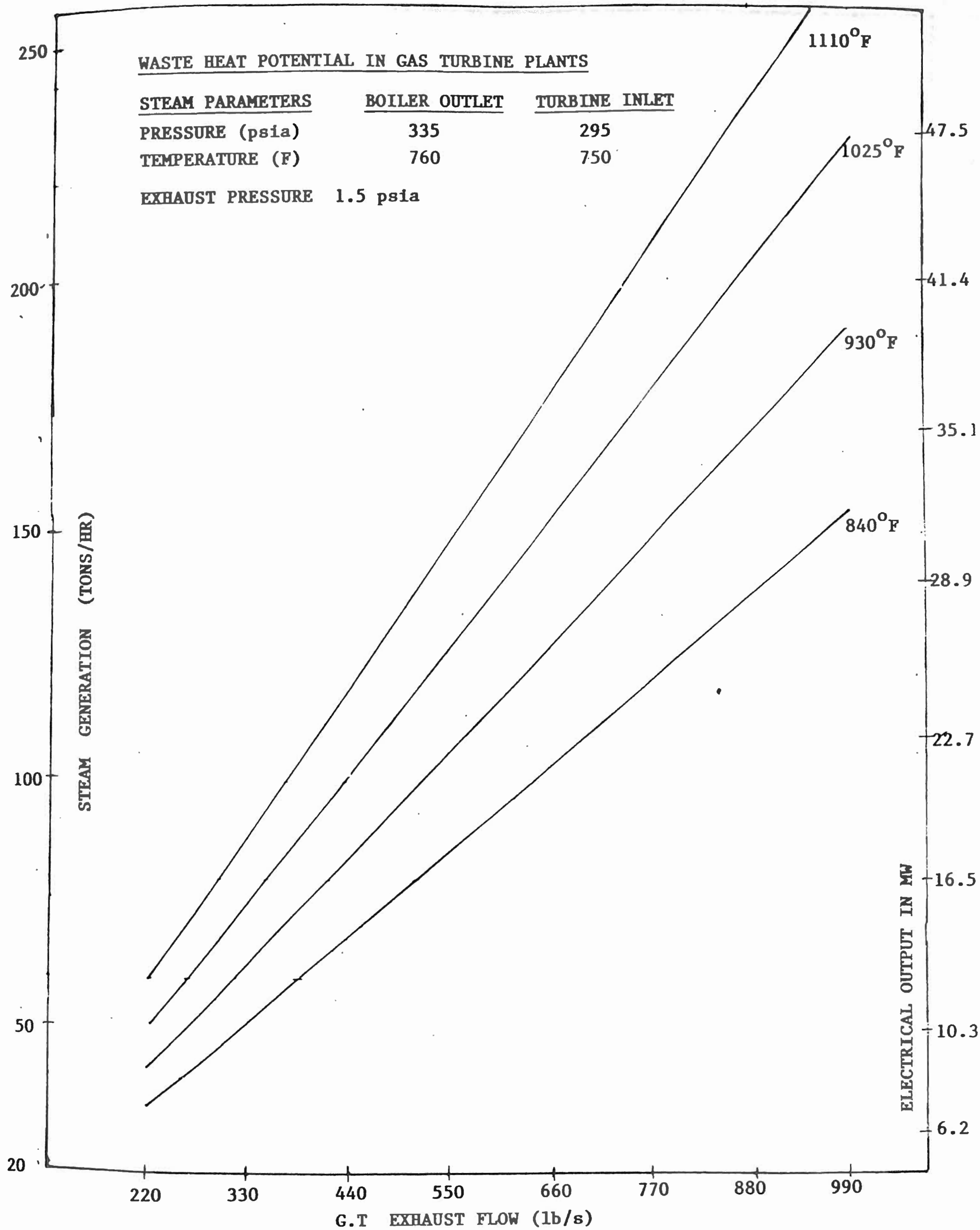


FIGURE 2.1 WASTE HEAT POTENTIAL IN GAS TURBINE PLANTS [9]

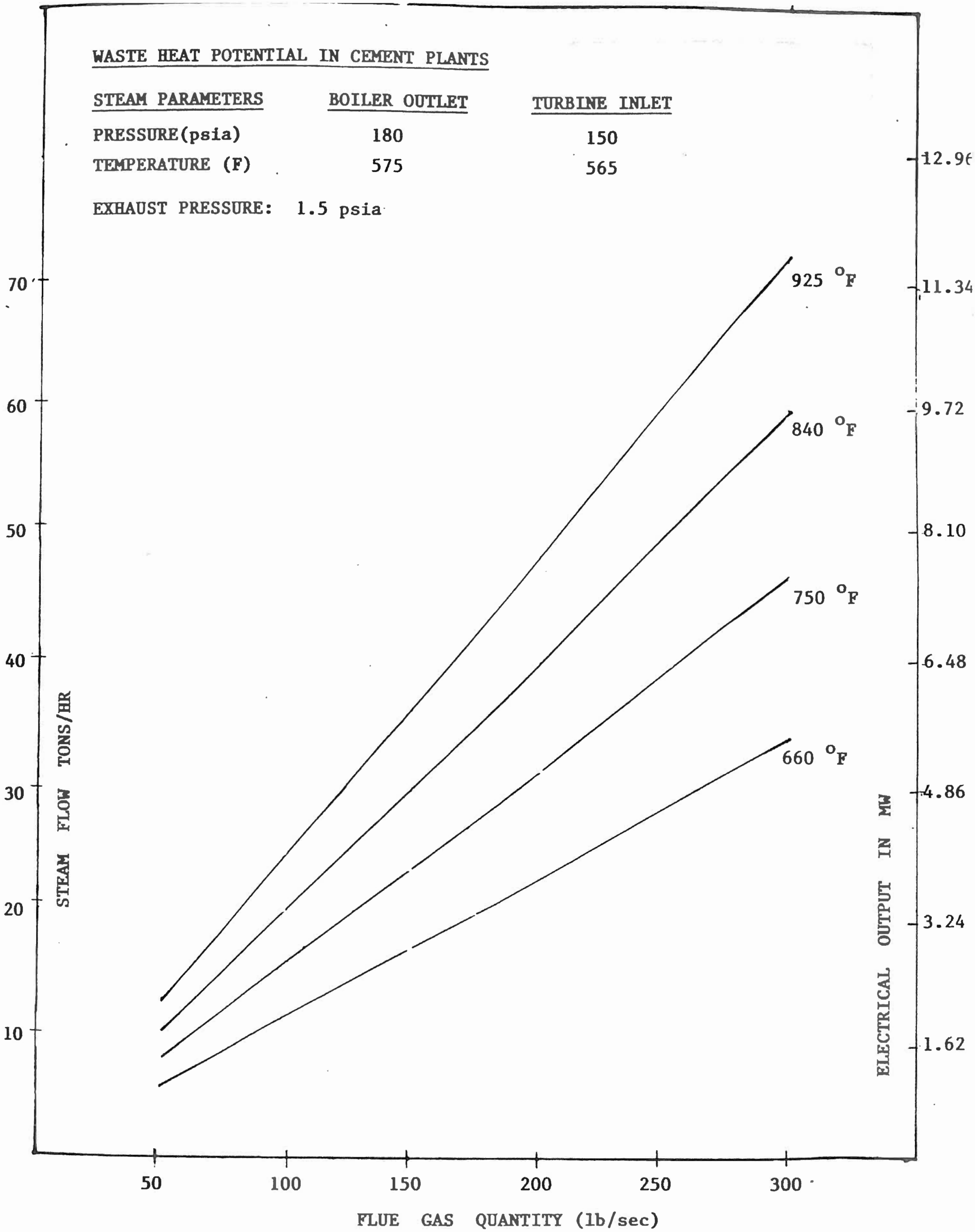


FIGURE 2.2 WASTE HEAT POTENTIAL IN CEMENT PLANTS [9]

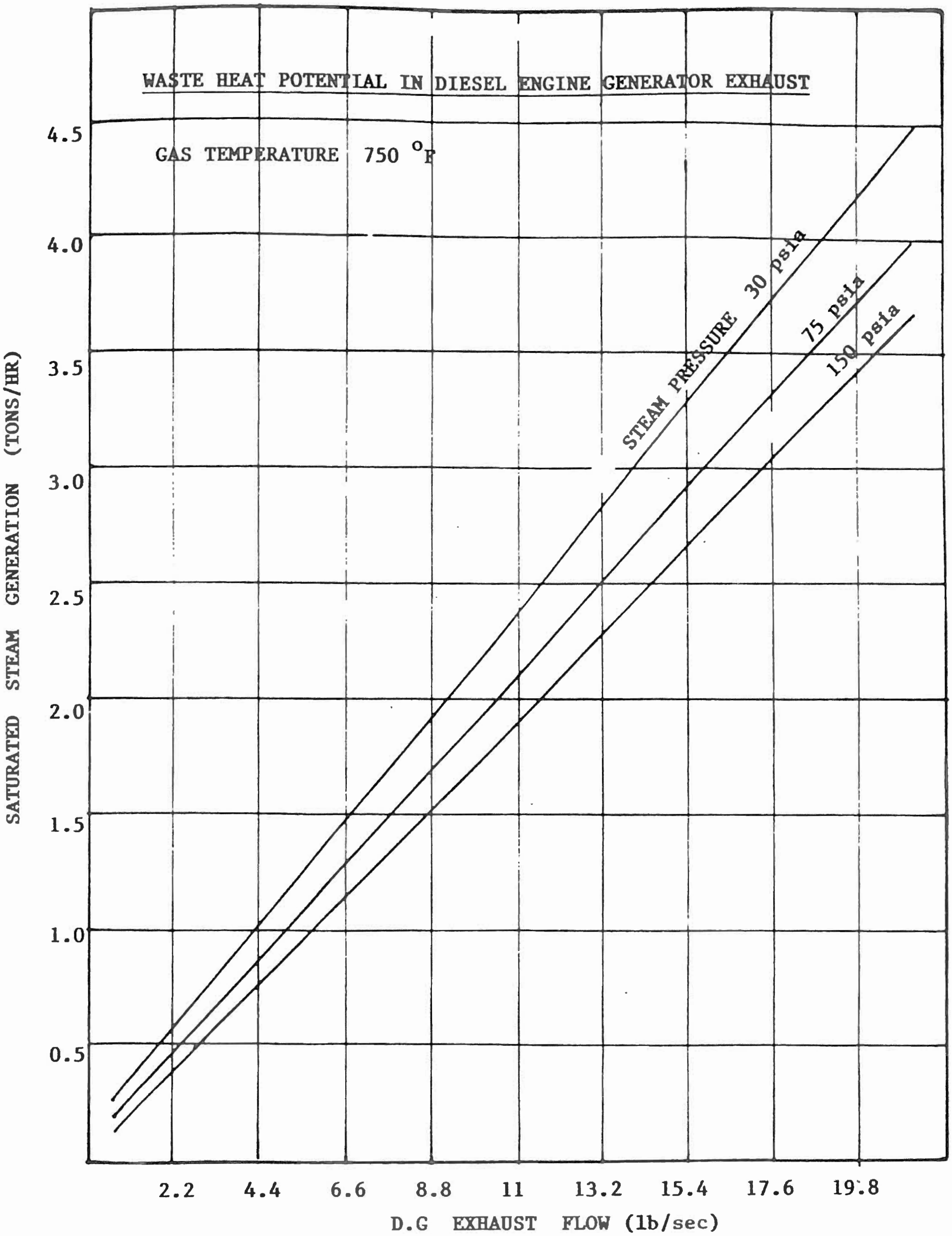


FIGURE 2.3 WASTE HEAT POTENTIAL IN DIESEL ENGINE GENERATOR EXHAUST [9]

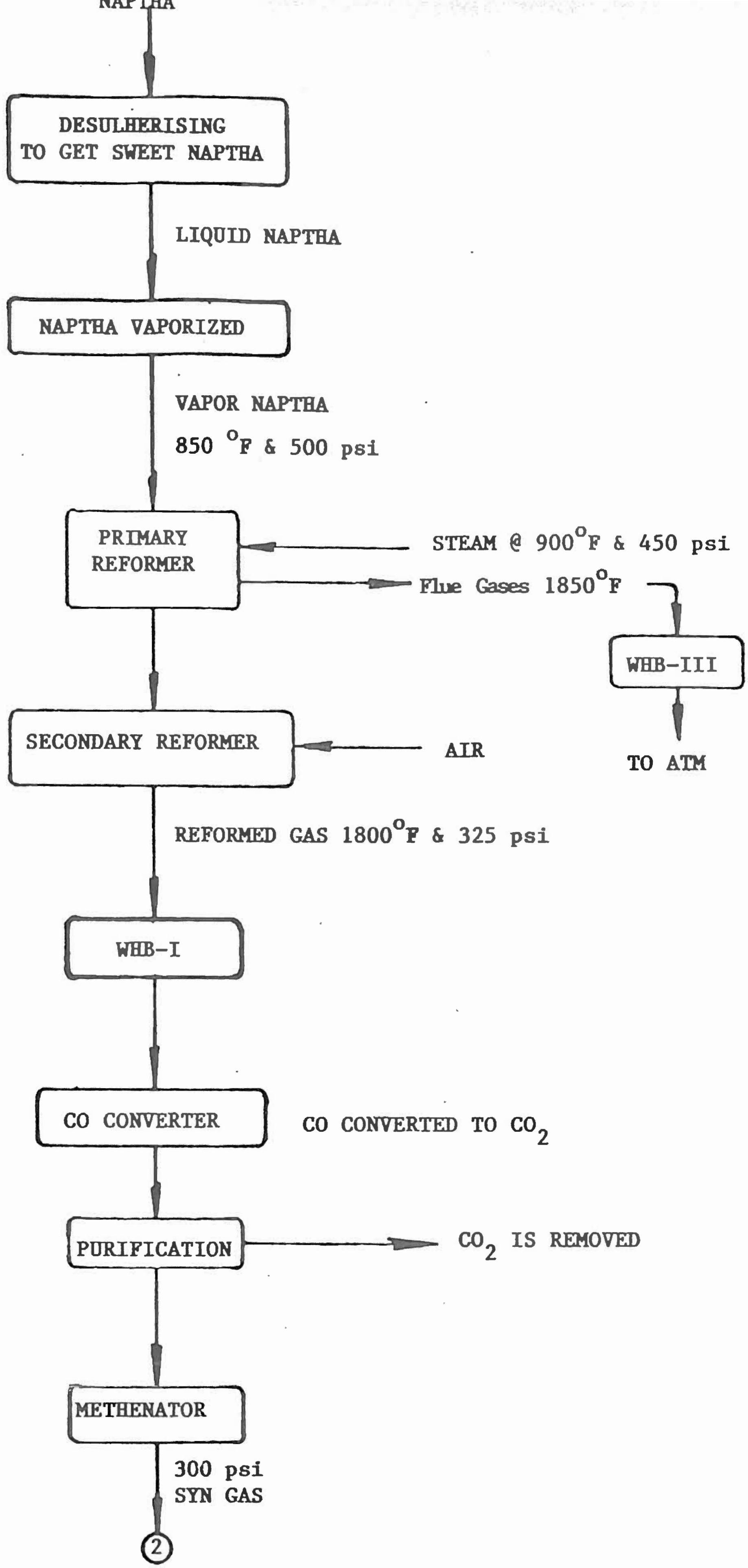


FIGURE 2.4 WASTE HEAT BOILERS IN A FERTILIZER PLANT [9]

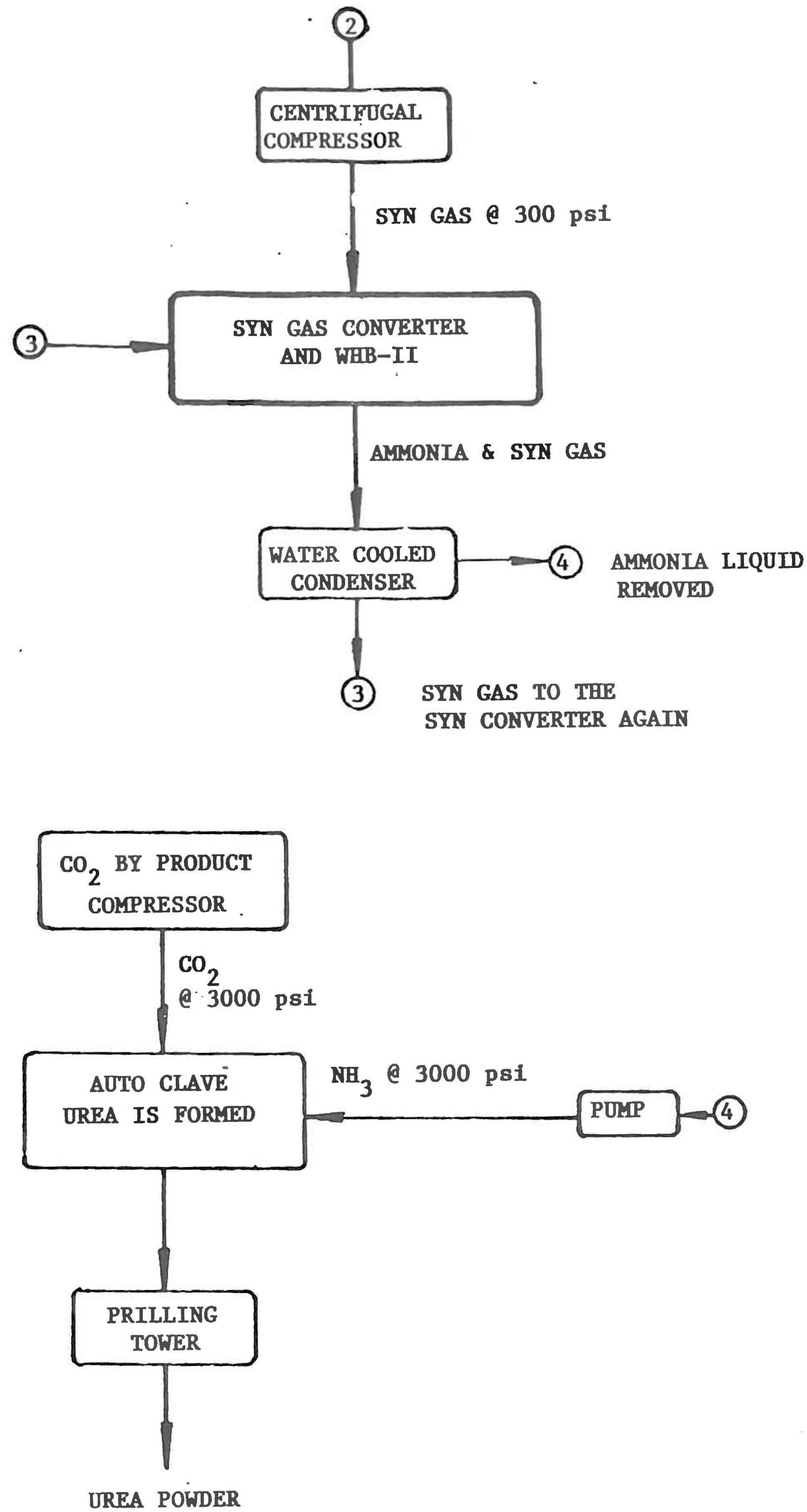


FIGURE 2.4 (contd.) WASTE HEAT BOILERS IN A FERTILIZER PLANT

Any repair or maintenance work on the Process Heat Recovery Boilers calls for a shut down of the total plant. Hence these boilers have to be designed with utmost care to keep down the maintenance time.

2.2.2 Waste Heat Boilers of II Category

Waste heat boilers of this category recover the heat which is otherwise wasted to atmosphere and generate steam at required parameters either for process use or for power generation. These boilers are always optional from the view point of cost economics of heat recovery. Waste heat recovery boilers of this category are generally used in combined cycle plants and cogeneration plants.

HRSGs in incinerator installations fall under this category. Because of shortages of landfill sites, more cities are turning to incineration as a means of disposing of municipal and household garbage. The design of HRSGs for these systems require a lot of care. The ash resulting from combustion of municipal solid waste (MSW) can contain a wide variety of metals, salts, silica, and alumina. Silica can be abrasive, so the flue gas velocity should not be high, usually in the range of 30 to 50 fps. Salts of sodium and chlorides of lead, zinc, and tin form a number of low melting eutectics with fusion temperatures in the range of 600 to 1600 °F. The gas temperature in the HRSG is usually in this range. Therefore, slagging can often result, leading to poor performance and corrosion of the HRSG. Widely spaced convection sections is a must to prevent slagging. HSGSs for

MSW are usually of the water tube type because of the cleaning and ash removal concerns.

2.3 HRSGs FOR COGENERATION AND COMBINED CYCLE APPLICATIONS

2.3.1 Cogeneration

Cogeneration means combined generation of electric power and useful heat, usually process steam, thus producing two forms of energy from one heat source. Cogeneration is alternatively termed as "Total Energy System". The important element a of cogeneration facility is the sequential use of energy. Thus, cogeneration attempts to make optimum use of available energy resources. Figure 2.5 shows the economic benefits of cogeneration system, compared to a conventional power plant. Figure 2.6 shows a typical skid mounted cogeneration system.

Cogeneration cycles can be broadly classified in two categories which are detailed below:

1. Topping Cycle Configuration

Topping cycles are those thermal cycles in which power is produced prior to the delivery of heat to the industrial plant. Gas turbine or Diesel engine generators with HRSGs fall under this category. Figure 2.7 illustrates the Gas turbine topping cycle configuration.

2. Bottoming Cycle Configuration

In bottoming cycles, thermal energy in the fuel is first utilized in some process, say a cement kiln and the heat in the exhaust form the kiln is utilized to generate process heat. Figure 2.8 illustrates steam turbine bottoming cycle configuration.

Gas turbines are widely used prime movers in both the low ends (< 5 MW) and in high ends (150 MW) of the power generation. They have several advantages such as high efficiency in the open cycle mode, low installed cost per kilowatt compared to other fossil and nuclear power plants, quick start-up capabilities, smaller space, and low cooling water requirements. Because of these advantages, the number of gas turbine installations with HRSGs are increasing year by year. The gas turbine HRSGs are discussed in greater detail in the following sections and the software "HGPRO" developed in this project is primarily for gas turbine systems.

2.3.2 Combined Cycle

Theoretically, the combination of any two or more power cycles is known as a combined cycle; the conventional form being the combination of gas turbine cycle (Brayton cycle) and steam turbine cycle (Rankine cycle). The gas turbine/ HRSG - steam turbine based combined cycle power plant is shown in Figure 2.9.

The main advantage claimed for combined steam and gas turbine cycles as compared to conventional steam power plant is higher overall thermal efficiency. The combined cycle causes minimal thermal pollution because of its high efficiency.

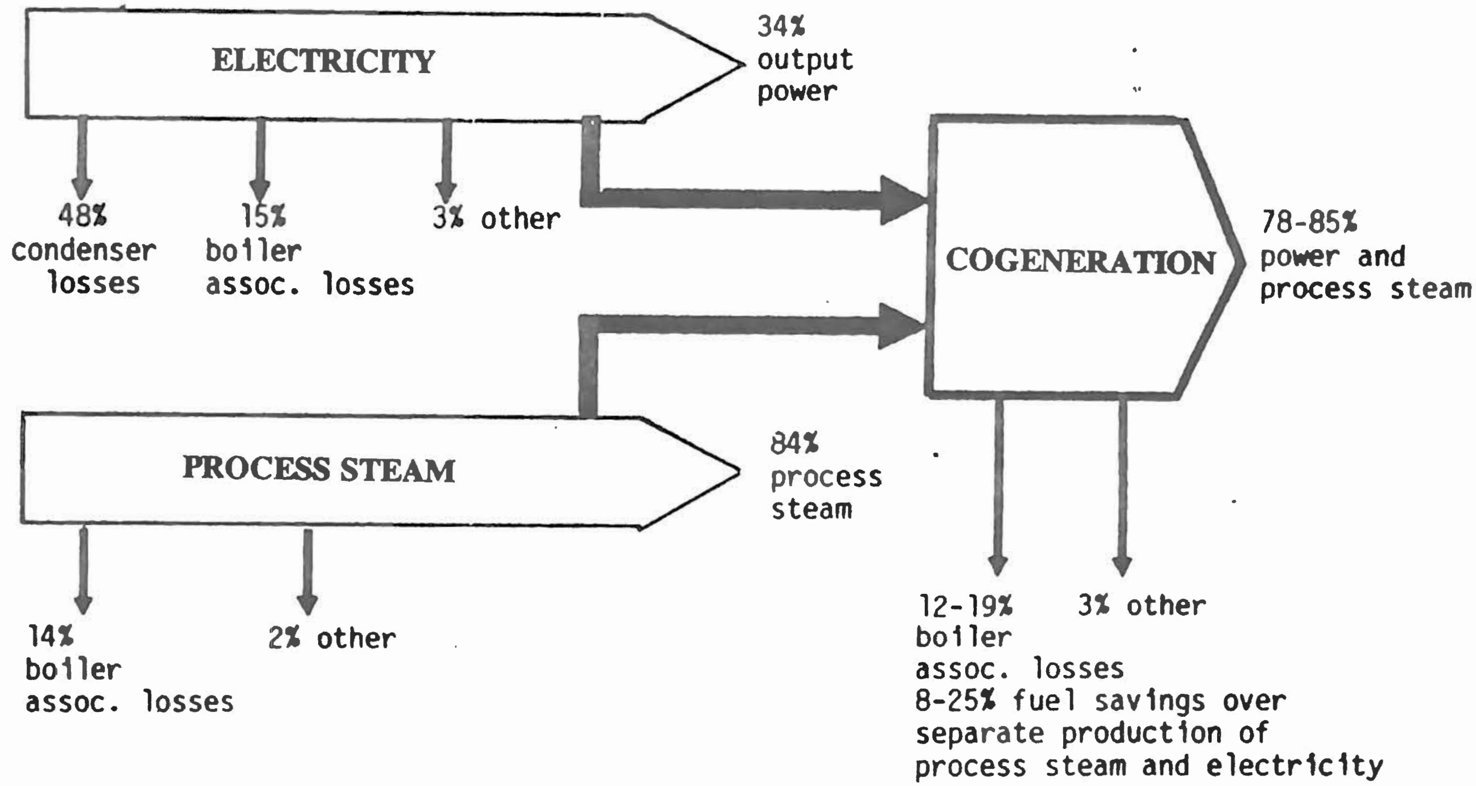


FIGURE 2.5 ECONOMIC BENEFITS OF A COGENERATION SYSTEM [10]

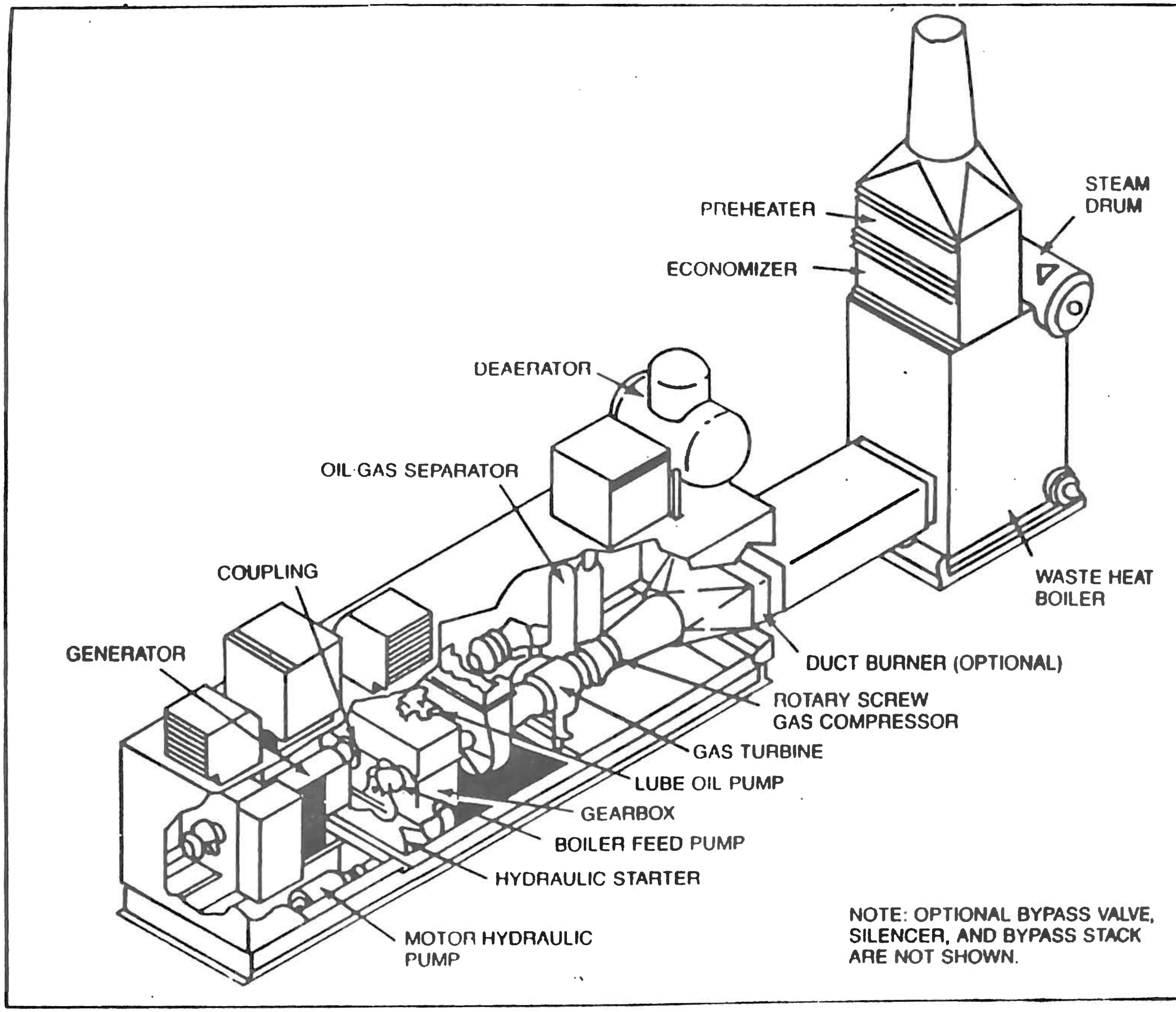


FIGURE 2.6 SKID MOUNTED COGENERATION SYSTEM

[SOURCE: Cogeneration - The Efficient Energy System of the ' 80s, Robert L. Mcvay, Specifying Engineer, April 1986, p 88]

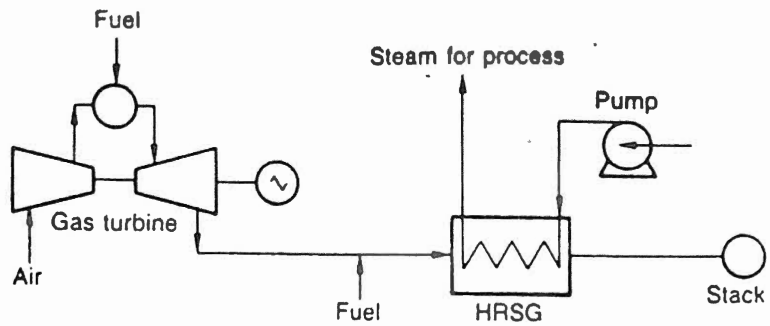


FIGURE 2.7 GAS TURBINE TOPPING CYCLE CONFIGURATION
[SOURCE: **HRSG Features and Applications**, V. Ganapathy, HPAC, January 1989, p 169]

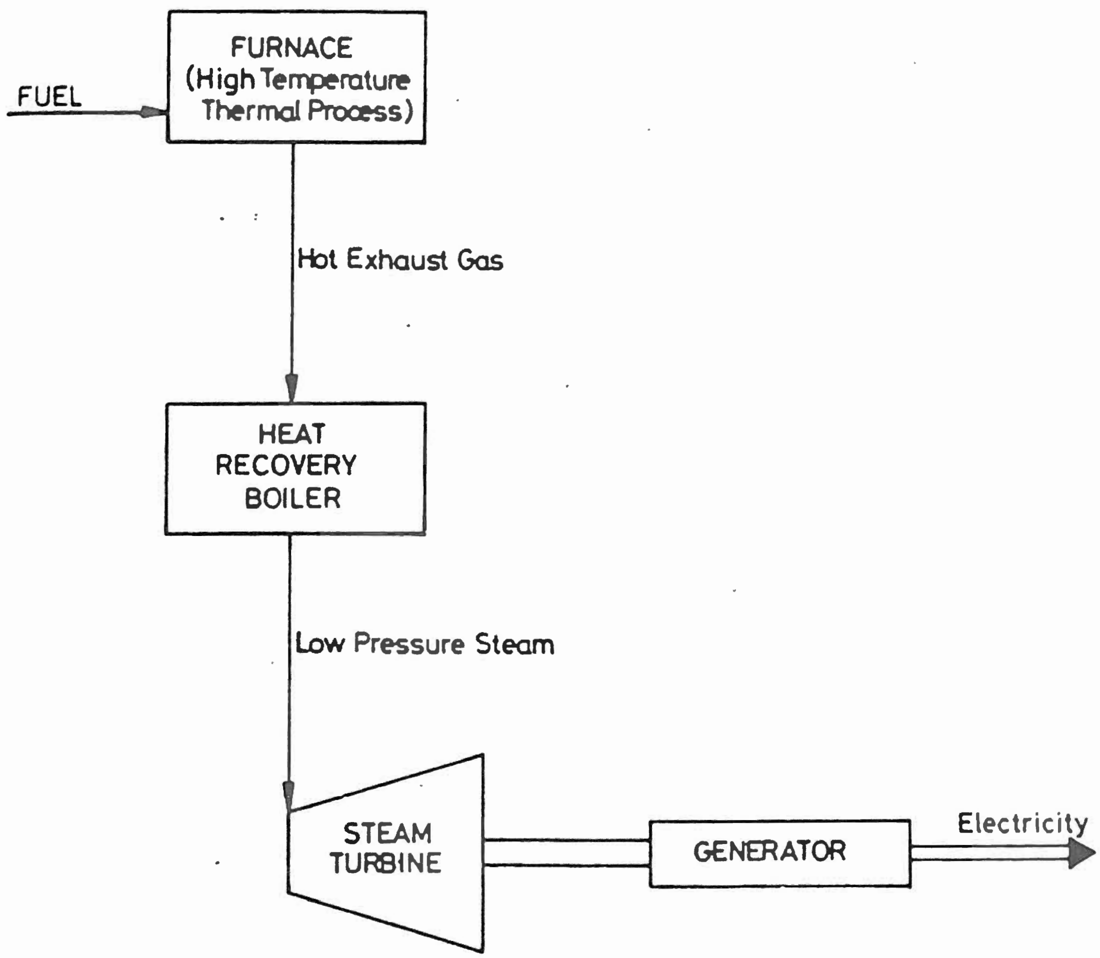


FIGURE 2.8 STEAM TURBINE BOTTOMING CYCLE CONFIGURATION [10]

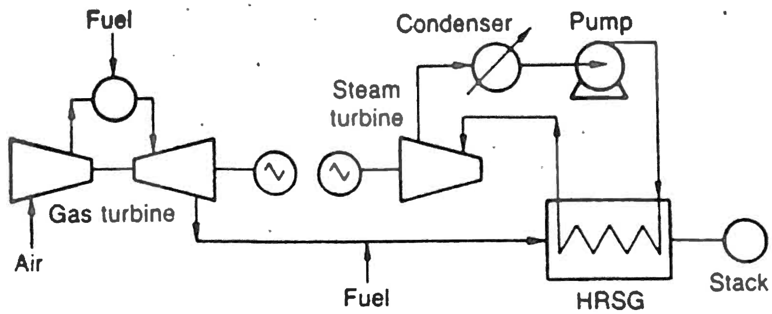


FIGURE 2.9 COMBINED CYCLE CONFIGURATION
[SOURCE: HRSG Features and Applications, V. Ganapathy, HPAC, January 1989, p 169]

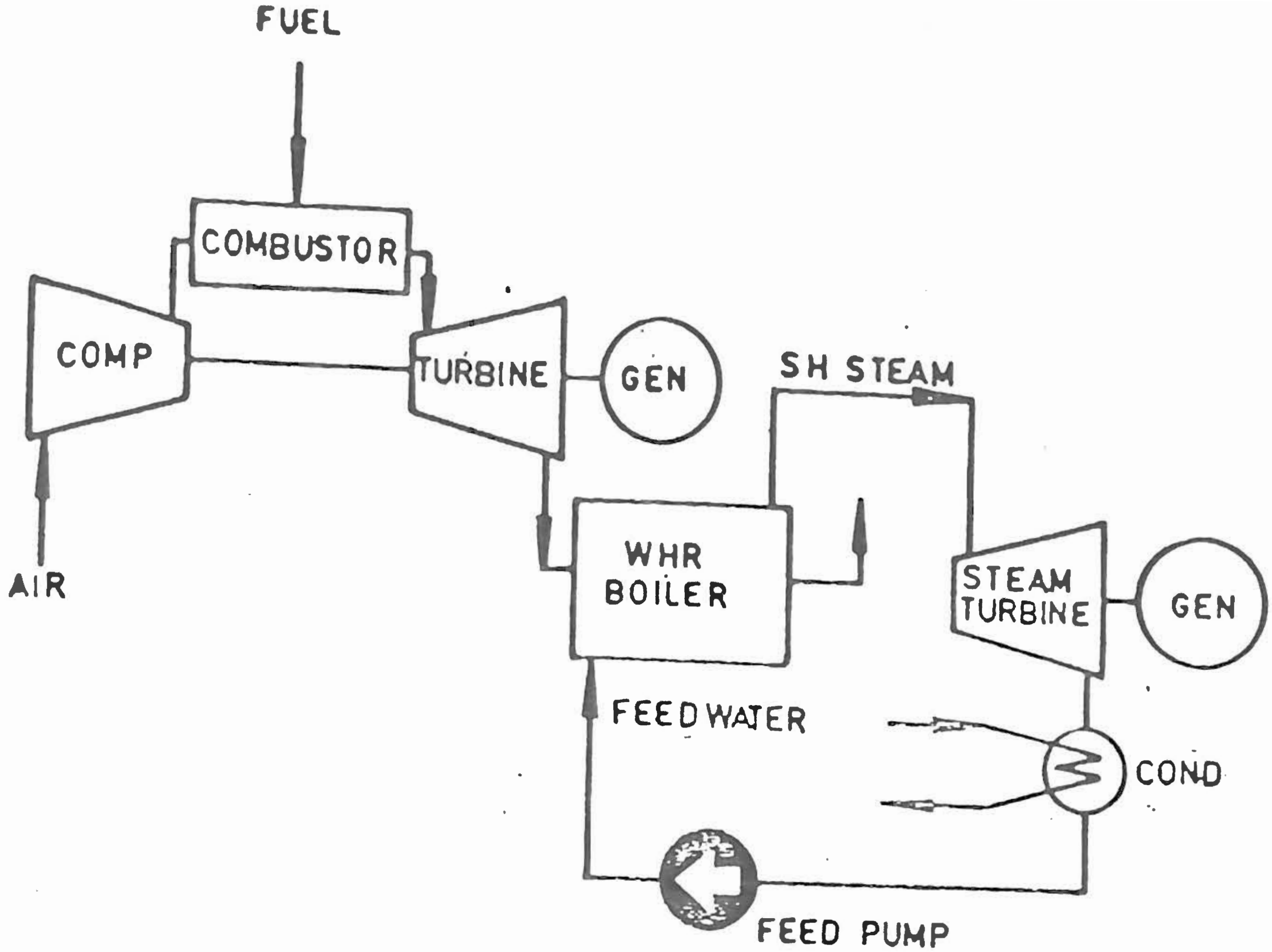
2.4 HRSGs for Gas Turbine Applications

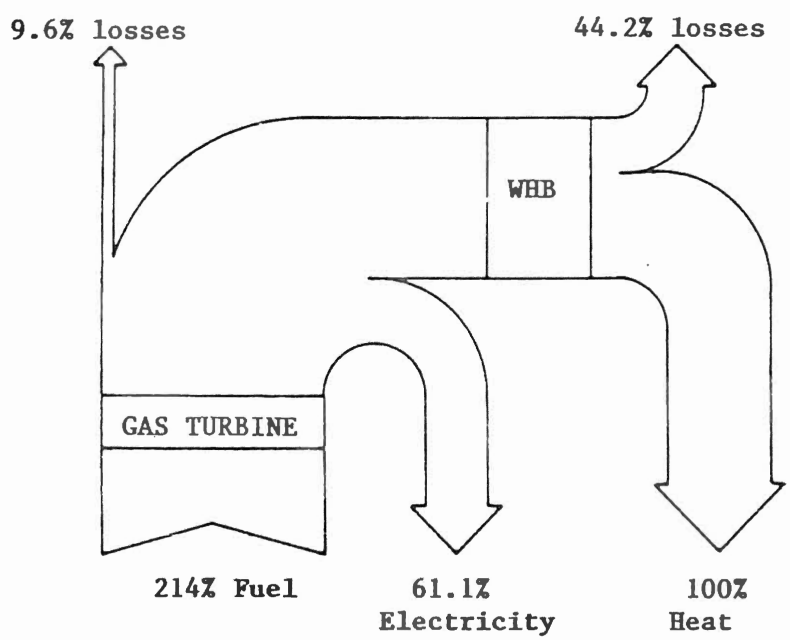
Gas turbine/HRSG installations may be categorized into four broad classifications, each of which is primarily dependent on how the steam generator is used in conjunction with the gas turbine. These categories are detailed below:

1. Gas turbine plus unfired steam generator
2. Gas turbine plus supplementary fired steam generator
3. Gas turbine plus furnace fired steam generator
4. Supercharged furnace fired steam generator plus gas turbine

2.4.1 Gas Turbine plus Unfired Steam Generator

In this type, an unfired steam generator is installed downstream of a gas turbine to recover the sensible heat energy in the G.T exhaust and supply steam to process or a steam turbine for additional power generation. This configuration is illustrated in Figure 2.10 All the fuel is fired in the gas turbine and the steam generator is entirely dependent on the gas turbine for its input. The steam generation pressure and degree of superheat are limited by the "Pinch Point" (discussed in chapter 3), which is the minimum temperature differential between steam/water and gas





POWER TO HEAT RATIO: 0.611
EFFICIENCY: 75%

FIGURE 2.10 GAS TURBINE + UNFIRED HRSG [9]

in the gas path which generally occurs at the evaporator/ economizer interface. Generally the steam pressures are limited to 850 psia and the superheat steam temperatures are limited to 750 °F.

With present gas turbine designs, the steam turbine would produce approximately 30 to 35% of the total plant output, with the remaining 65-70% being produced by the gas turbine. Since, the power from the steam turbine would be produced without any additional fuel input and since there is only a small decrease in gas turbine efficiency because of the back pressure of the steam generator, the overall plant thermal efficiency would be improved over that of open cycle gas turbines.

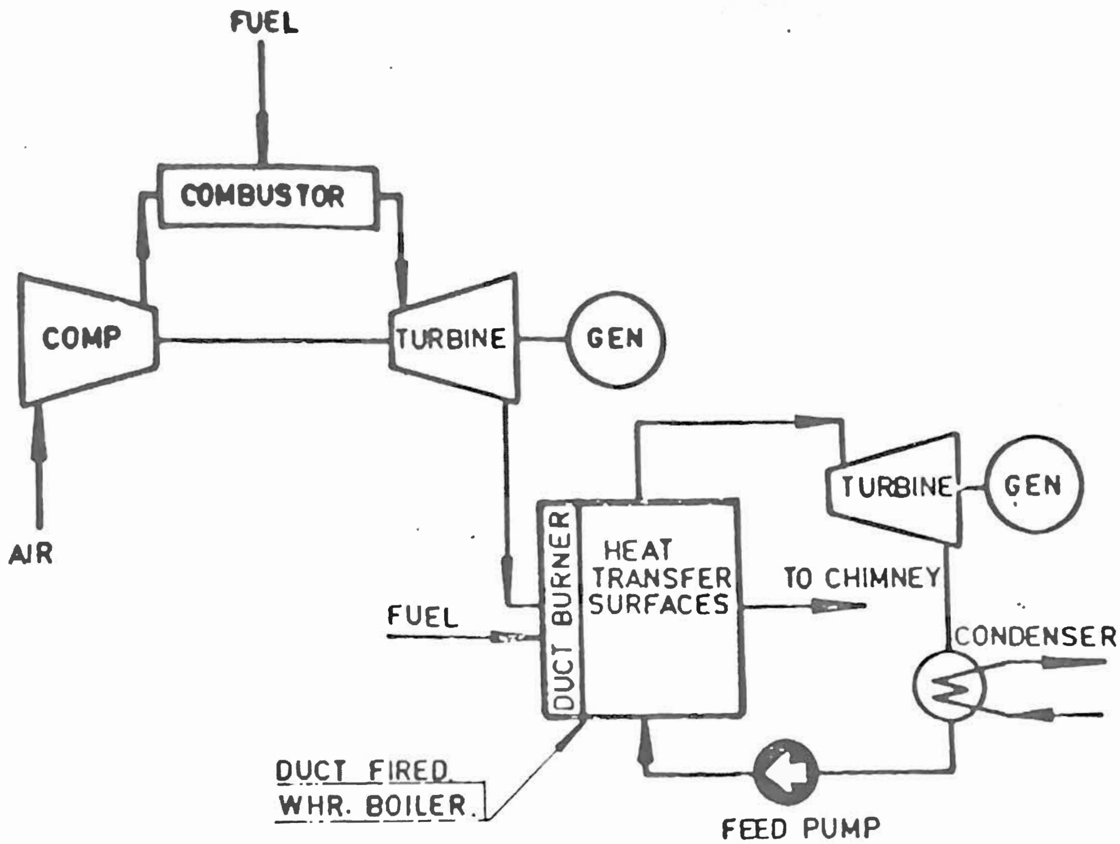
2.4.2 Gas Turbine plus Supplementary Fired Steam Generator

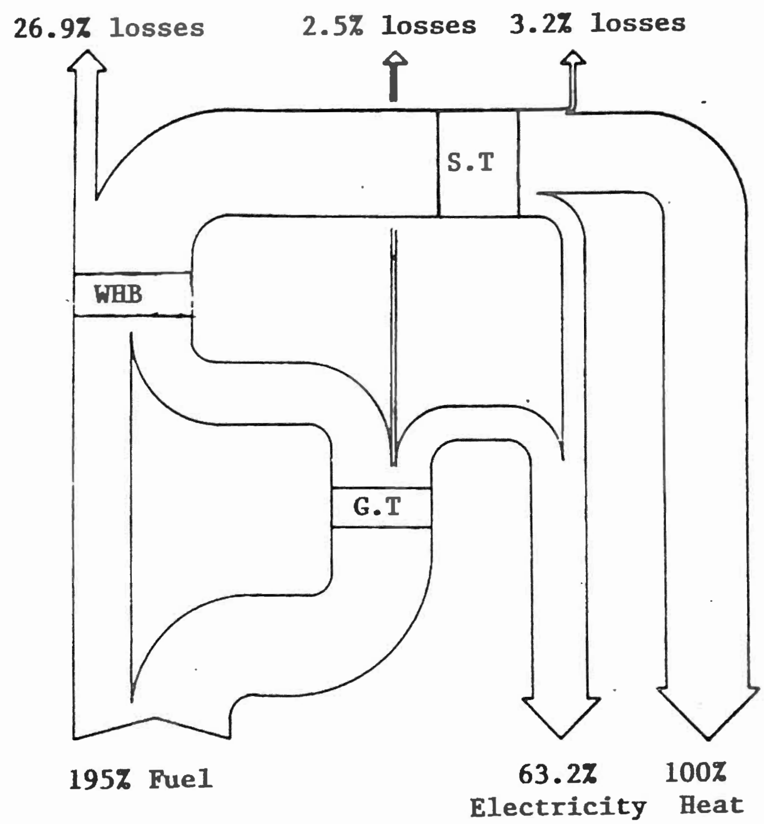
Gas turbine exhausts contain 14 to 16% oxygen by volume and may be used as an oxygen source to support further combustion. Therefore, supplementary fired systems consist of a gas turbine and an unfired HRSG along with the supplementary firing (SF) system located in the duct between the gas turbine and the steam generator. The supplementary firing system utilize a portion of the oxygen in the gas turbine exhaust and the maximum temperature of flue gas coming out of the firing system is limited to about 1650 °F, considering the state-of-art duct burners. By maintaining this maximum gas temperature level, the steam generator retains its relatively simple arrangement. This configuration is illustrated in Figure 2.11. With the given gas turbine size and this temperature limit, the steam generation can be doubled that of an unfired HRSG, and the steam turbine supply a greater proportion of the plant electrical load. For most current designs, the steam turbine would supply approximately 50% of the total electrical output. The steam turbine designs employed in this application are generally of non reheat and condensing type.

2.4.3 Gas Turbine plus Furnace Fired Steam Generator

Current gas turbines operate with 300 to 400% excess air and this gas turbine exhaust can support further combustion of approximately four times as much as fuel in steam generator as in the gas turbine. The majority of the fuel can now be fired in the steam generator and 70 to 85% of the total plant load can be met by steam turbine. *An excellent example of this type of installation can be found in the OG&Es horse-shoe lake power plant in Oklahoma.*

The gas turbine, in this case, is considered to be an independent power supplier and a forced draft fan for the steam generator. The previous constraint imposed by the low gas turbine exhaust temperature is now eliminated and any of the high pressure, high temperature steam conditions utilized by modern steam turbines can be incorporated into the combined cycle. The gas turbine fuel in the previous arrangement is presently limited to gas and oil. This design, however, allows the use of any fossil fuel in the steam generator portion of the cycle, although the majority





POWER TO HEAT RATIO: 0.632
EFFICIENCY: 83.4%

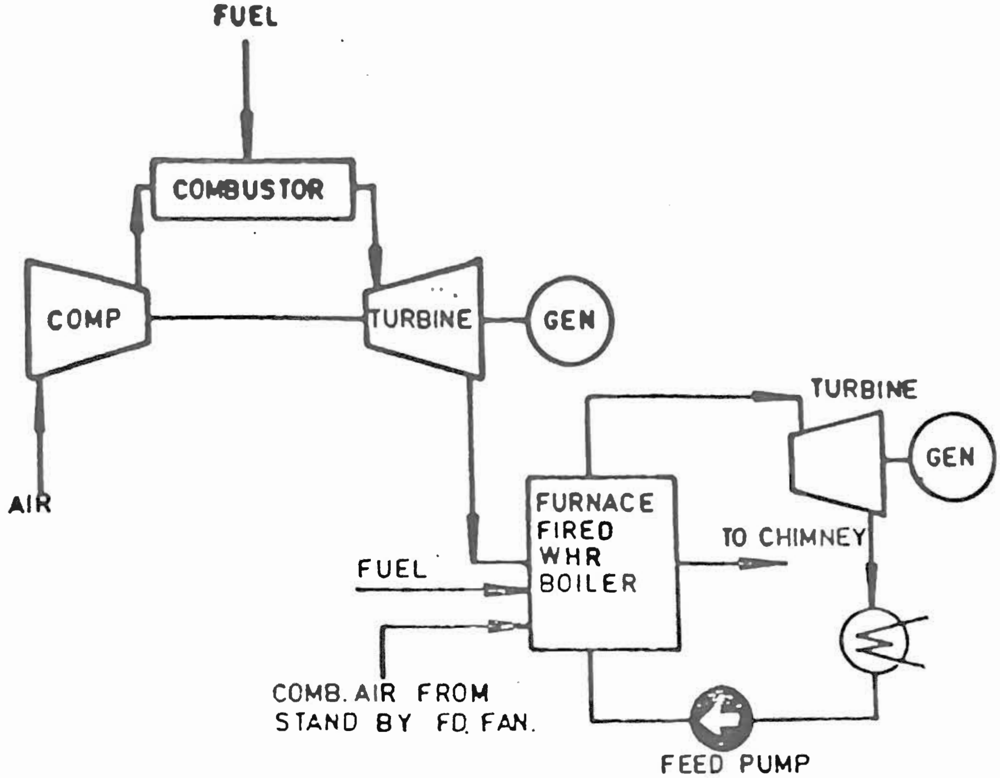
FIGURE 2.11 GAS TURBINE + SUPPLEMENTARY FIRED HRSG [9]

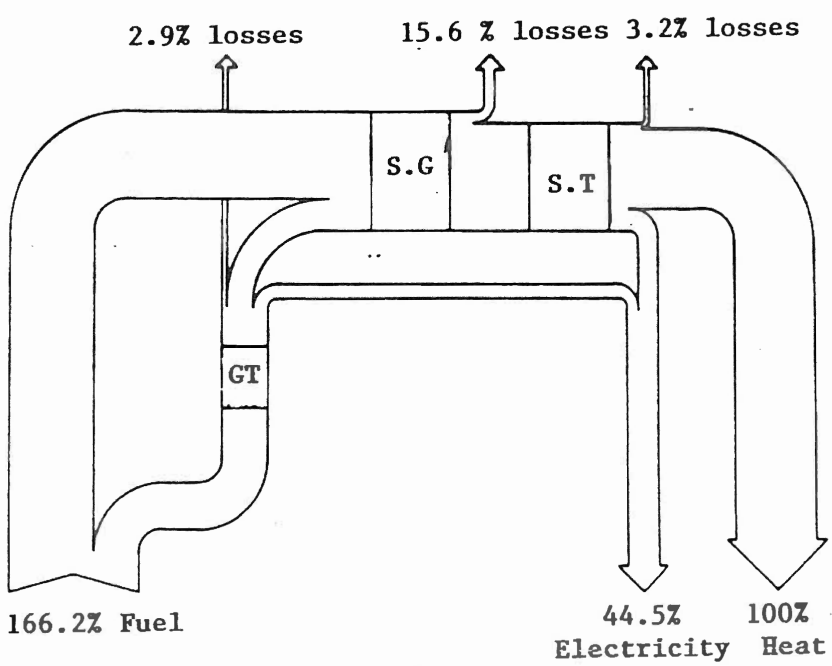
of installations of this type to date have been designed for gas or oil firing.

With the above approach, as much as 4 to 5% increase in plant thermal efficiency is possible. This configuration is illustrated in Figure 2.12.

2.4.4 Supercharged Furnace Fired Steam Generator plus Gas Turbine

Another possible configuration for gas turbine/HRSG includes the installation of a steam generator between the air compressor and the gas turbine. The air compressor serves as a forced draft fan and pressurizes the boiler where all the fuel is fired, the products of combustion having been partially cooled in the boiler, are then discharged through a gas turbine. Additional heat exchangers are installed at the exhaust if the gas turbine to be used as economizers or feed water heaters. The majority of the plant electric generation is supplied by steam turbine with the gas turbine selected to provide either sufficient power to drive the air compressor or sized to supply additional electric power.





POWER TO HEAT RATIO: 0.445
EFFICIENCY: 86.9%

FIGURE 2.12 GAS TURBINE + FURNACE FIRED HRSG [9]

CHAPTER - 3 HRSG ANALYSIS ROUTINE - HGPRO

3.0 INTRODUCTION

Engineers and Consultants involved in Cogeneration and Combined Cycle plant evaluation and cycle studies often come across the problem of determining the Design Temperature Profile (gas and steam-water temperature profile) in the HRSG and the resulting steam generation. Although the final selection of these parameters is determined by the size and the cost of the HRSG, engineers are often confronted with the problem of determining these parameters during the project feasibility study and early engineering phases.

The Design Temperature Profile (DTP) is the basis for sizing an HRSG. Once the profile is determined, the heating surface areas of the superheater, evaporator, economizer, and condensate preheater can be determined. This can provide initial input for the cogeneration analysts for arriving at an budgetary estimate of the HRSG during the initial evaluation of the project.

A computer program titled "HGPRO" has been developed and presented in detail in the following sections. The routine "HGPRO" can be used to acquire information on the steam generation capacity and DTP of any HRSG behind a gas turbine without actually sizing the tube or fin configuration. Also, the power generation potential from the steam generated in HRSG can be calculated for an unfired case.

However, it is likely that actual HRSG performance values will be somewhat different than the initial values obtained above. Reasons for these performance variations include:

- Changes in the ambient conditions. Gas turbine exhaust conditions, such as exhaust gas flow rate, temperature, and gas analysis, are impacted by ambient temperature. Usually, gas turbine manufacturers provide all these parameters at the ISO conditions.
- Changes in gas turbine load from original design.
- Changes in exhaust-gas heat content. Enthalpy of the exhaust gas is affected by many different variables including the fuel composition.

One method of predicting the actual performance within a range is to obtain all the related gas turbine data and fuel data from other installations in the same region or from other regions which have atmospheric and other operating conditions similar to the installation area in question.

3.1 TEMPERATURE PROFILES

An HRSG may deliver steam at a single pressure or may produce steam at two or more pressure levels. Multi-pressure steam production is useful and economical only if the steam at the various pressure levels can be utilized. When a multi-level pressure boiler cannot be justified, then selecting the lowest possible usable pressure level (in the process) for steam generation will achieve the highest steam production and the greatest heat recovery. In the case of combined cycle, a detailed stage by stage analysis is required for arriving at the optimum pressure and temperature levels for steam generation. (though, steam at highest pressure and temperature would yield the maximum electrical power, the application may result in high equipment costs and neccesiates a techno-economic optimization for arriving at the appropriate steam generation pressure and temperature).

Typical gas and steam temperature distribution in HRSGs is shown in figure 3.1 for a simple unfired case. The heat recovery at various steam pressures is depicted in figure 3.2 for a simple unfired case. The pinch point and the approach point are two important parameters which affect the cost and effectiveness of any specified heat exchanger section within the HRSG system. The pinch and approach points are detailed below:

3.1.1 Pinch Point (PP)

Pinch Point is the difference between the gas temperature leaving the evaporator section of the system and the saturation temperature corresponding to the steam pressure in that section, measured in degrees F.

Lowering the pinch point increases the heat recovery and hence the steam production. However, the amount of heat transfer surface area required increases very rapidly as the pinch point decreases due to the low log mean temperature difference. This subsequently increases the cost of the HRSG and gas side draft loss. It is desirable to keep the gas side draft loss as low as possible, because the gas turbine loses roughly 1 % of its power generating capacity for every 4 in WG of back pressure. Hence multiple computations are required to select the most optimum pinch point. An economical pinch point is around 20 to 25 °F.

3.1.2 Approach Point (AP)

Approach Point is the difference between the saturation temperature of the water/steam and the water temperature leaving the economizer measured in degrees F.

Lowering the approach temperature can result in more steam production at that pressure level. As with lower pinch point, this can only be realized at a higher cost and some increase in draft loss. Higher approach temperatures are generally prescribed for design stability. The higher approach temperature will increase the surface in the evaporator section and assure a higher level of stability.

In an economizer section a higher approach temperature will reduce steaming in the economizer at lower loads and during initial start-up. This effect will have to be assessed as adequate means should be incorporated to relieve the steam formed and prevent damage to the economizer if steaming is expected to occur often. Summarizing, an optimum approach point has to be selected based on the control load range required for a specific application. Usually, the approach point varies between 10 to 45 °F.

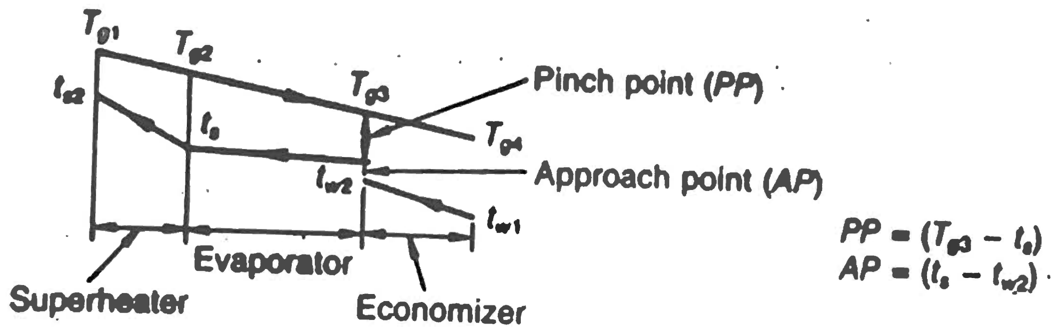


Figure 3.1 Gas and Steam Tempearture Distribution in HRSGs

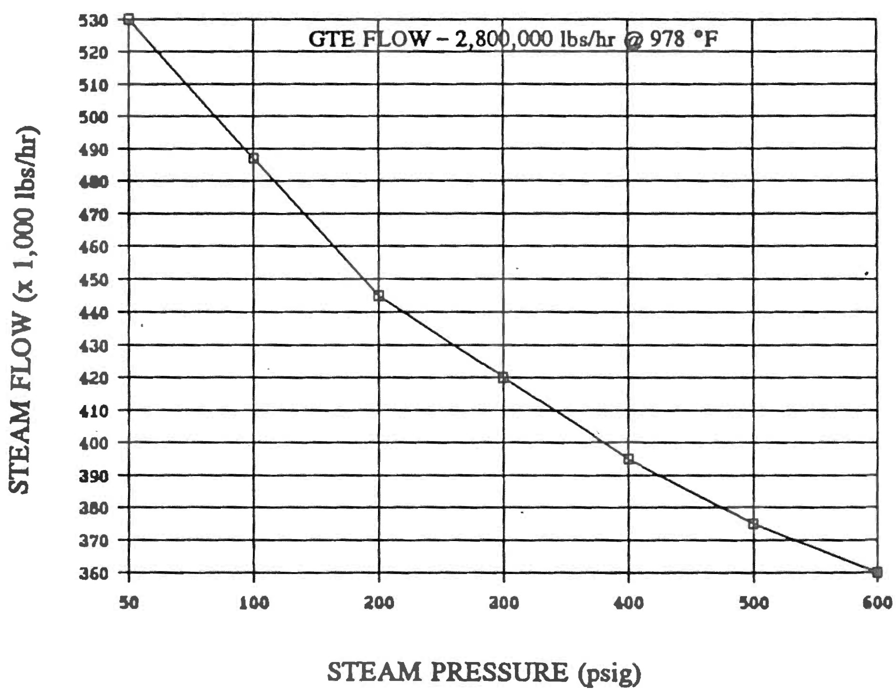


Figure 3.2 Heat Recovery at Various Steam Pressures [6]

3.1.3 Stack Temperature

Lower stack temperatures result in more heat recovery but introduce concerns related to:

a. Acid Dewpoint Corrosion: Trace quantities of sulfur present in the natural gas will produce sulfur trioxide and present some potential for localized sulfuric acid corrosion in colder sections of the heat transfer modules. Mullers graph or other correlations are used to find the acid dewpoint. Care must be taken to exhaust the gases at temperatures higher than the dewpoint at all loads. When sulphur is absent in the fuel, acid dew point is not a concern at all.

b. Water Dewpoint Corrosion: Moisture will be present in considerable quantities in the gas turbine exhaust due to steam/water injection for NOx reduction and steam injection in selected cases for power production. Operation of sections of the carbon steel heat transfer surfaces, below the water dewpoint will lead to accelerated corrosion.

It is necessary that both acid and water dewpoint corrosions are considered in detail during the early design phase to avoid potential operational/maintenance problems of a HRSG installation. Further discussion on this topic may be found in references [12] and [13].

Depending on the gas side temperature profiles in the main section, a Condensate Preheater may be added for enhancing the heat recovery.

3.2 DESIGN AND PERFORMANCE PARAMETERS

The variables which have influence over the HRSG design and performance can be categorized as input, design and output variable.

Input variables consist of:

Gas Turbine Exhaust Flow Rate and Temperature.

Gas Turbine Exhaust Constituents

Feed Water Temperature

Blowdown Rate

Design parameters which are either assumed or calculated include:

HRSG Geometry

Heat Transfer Coefficient

Thermal Losses

Gas Leakage

Output Variables which influence the HRSG are:

Steam Pressure, Steam Temperature, and Steam Quality

The importance of some of these parameters on the HRSG design is best illustrated by an example which is given in the following section.

3.3 ILLUSTRATIVE EXAMPLE

GIVEN:

GAS TURBINE DATA, SPECIFIC HEAT DATA, HRSG DESIGN CONDITIONS, AND STEAM TURBINE DATA.

TO COMPUTE:

STEAM GENERATION QUANTITY, DUTIES OF SUPERHEATER, EVAPORATOR & ECONOMIZER SECTIONS, GAS AND STEAM/WATER TEMPERATURE PROFILE IN DIFFERENT SECTIONS OF HRSG, POWER OUTPUT FROM STEAM TURBINE.

GAS TURBINE DATA:

EXHAUST TEMPERATURE : 920 °F

EXHAUST FLOW RATE : 525,000 lb/hr (145.8334 lb/sec)

SPECIFIC HEAT DATA:

Temperature (°F)	Specific Heat (Btu/lb-°F)
300	0.2550
400	0.2580
500	0.2610
600	0.2640
700	0.2670
800	0.2700
900	0.2730
1000	0.2760

HRSG DESIGN CONDITIONS:

STEAM PRESSURE AT MAIN STEAM STOP VALVE : 600 psig

STEAM TEMPERATURE AT MAIN STEAM STOP VALVE : 757 °F

FEED WATER TEMPERATURE : 240 °F

PINCH POINT : 22 °F

APPROACH POINT : 18 °F

PRESSURE LOSS IN VALVES + LINES + SH COILS : 24 psig

BOILER BLOWDOWN : 3.0 %

MODE OF OPERATION : UNFIRED

STEP 1

Calculate Drum Operating Pressure (DOP)

= Steam Pressure at MSSV + Losses
= 600 psig + 24 psig
= 624 psig

STEP 2

Fix t_{sat} and obtain tf_2 and TG_3

The ASME steam formulations have been coded in BASIC language and are used in "HGPRO" to obtain the various state points for steam. The program is well documented and the codes are self explanatory. However, for the calculations shown here, all the values have been taken from steam tables.

t_{sat} corresponding to DOP (624 psig) = 493.2 °F

$tf_2 = t_{sat}$ - Approach Point
= 493.2 °F - 18 °F
= 475.2 °F

$TG_3 = t_{sat}$ + Pinch Point
= 493.2 °F + 22 °F
= 515.2 °F

STEP 3

Calculate the enthalpy of exhaust gas at the inlet to boiler and at evaporator/economizer interface.

From the specific heat data, through interpolation,

Specific Heat at TG_1 (920.0 °F) = 0.2736 Btu/lb-°F

Specific Heat at TG_3 (515.2 °F) = 0.2615 Btu/lb-°F

STEP 4

Calculate the steam generation possible through energy balance across the superheater/economizer sections.

Enthalpy of exhaust gas at TG_1

= HG_1
= TG_1 x specific heat of exhaust gases at TG_1
= 920 °F x 0.2736 Btu/lbm
= 251.71 Btu/lbm

Enthalpy of exhaust gas at TG_3

= HG_3
= TG_3 x specific heat of exhaust gases at TG_3
= 515.2 °F x 0.2615 Btu/lbm-°F
= 134.73 Btu/lbm

Heat available for steam generation

= QG_{13}
= 0.93 x Gas mass flow rate/sec x 3,600 x (HG_1 - HG_3)
= 0.93 x 145.833 lbm/s x 3,600 s/hr x (251.71-134.73) Btu/lbm
= 57,115,511 Btu/hr

Enthalpy of feed water at tf_2 (475.2 °F) and DOP (624 psig)

= HCL
= 458.66 Btu/lbm

Enthalpy of steam at MSSV (757 °F and 600 psig)

= HTP
= 1,382.91 Btu/lbm

With the energy and mass balance across the SH/EVA surfaces,

Steam Generation potential (STGEN) is as follows:

Steam Generated

= QG_{13}/(HTP-HCL)
= 57,115,511 Btu/hr / (1,382.91 - 458.66) Btu/lbm
= 61,797 lbm/hr

STEP 5

Find the gas side enthalpy drop in the SH/EVA sections and

find ETG_2

Enthalpy of steam at saturation point

= HGT
= 1,203.63 Btu/lbm

Superheater Duty

= QSH
= STGEN x (HTP - HGT)
= 61,797 lbm/hr x (1,382.91 - 1,203.63) Btu/lbm
= 11,078,966 Btu/hr
= 11.08 Million Btu/hr.

Gas side enthalpy drop in the superheater section

= ENTHDRO
= Q_{SH} / (0.96 x gas mass flow rate x 3,600)
= 11,078,966 Btu/h / (0.96 x 145.833 lbm/s x 3,600 s/hr)
= 21.98 Btu/lbm

Enthalpy of exhaust gas at the entry to evaporator

= $ENTHG_2$
= (EGT_1 x CPG) - ENTHDRO
= (920 °F x 0.2736 Btu/lbm-°F) - 21.98 Btu/lbm
= 229.73 Btu/lbm

Temperature of exhaust gas at the entry to evaporator

= EGT_2
= 846 °F

[The temperature is obtained iteratively using the relation

CPG = 0.258 + 0.00003 x (EGT_2 - 400)] Btu/lbm-°F

STEP 6

Calculate the Evaporator duty

Evaporator duty

= Q_{EVA}
= STGEN x (HGT - HCL)
= 61,797 lbm/hr x (1,203.63 - 458.66) Btu/lbm
= 46,036,911 Btu/hr
= 46.04 Million Btu/hr

STEP 7

Calculate the Economizer duty

Water flow through the economizer

= WATFLO
= 1.03 x STGEN
= 1.03 x 61,797 lbm/hr
= 63,651 lb/hr

Enthalpy of feed water (240 °F and 624 psig)

= HCL_2
= 209.65 Btu/lbm

Economizer duty

= QECO
= WATFLO x ($HCL - HCL_2$)
= 63,651 lbm/hr x (458.66-209.65) Btu/lbm
= 15,849,736 Btu/hr
= 15.85 Million Btu/hr

STEP 8

Find the temperature of the exhaust gases at the exit of economizer.

Enthalpy drop of exhaust gases across the economizer surface

= ENTHECO
= QECO / (0.96 x EGTF x 3,600 s/hr)
= 15,849,736 Btu/h / (0.96 x 145.833 lbm/s x 3,600 s/hr)
= 31.45 Btu/lbm

Enthalpy of exhaust gases at the economizer exit

= HG_4
= HG_3 - ENTHECO
= 134.73 Btu/lbm - 31.45 Btu/lbm
= 103.28 Btu/lbm

Temperature of exhaust gases at the economizer exit

= TG_4
= 400 °F

STEP 9

Check for proper Pinch Point

It can be shown from a simple energy and mass balance that the pinch point cannot be selected arbitrarily because two conditions must be met to arrive at a feasible cycle.

For steam generation to occur:

$$tg_3 > t_{sat} \text{ and } TG_4 > tf_1$$

In this example

$$tg_3 = 515.2\ °F$$

$$t_{sat} = 493.2\ °F$$

$$TG_4 = 400.0\ °F$$

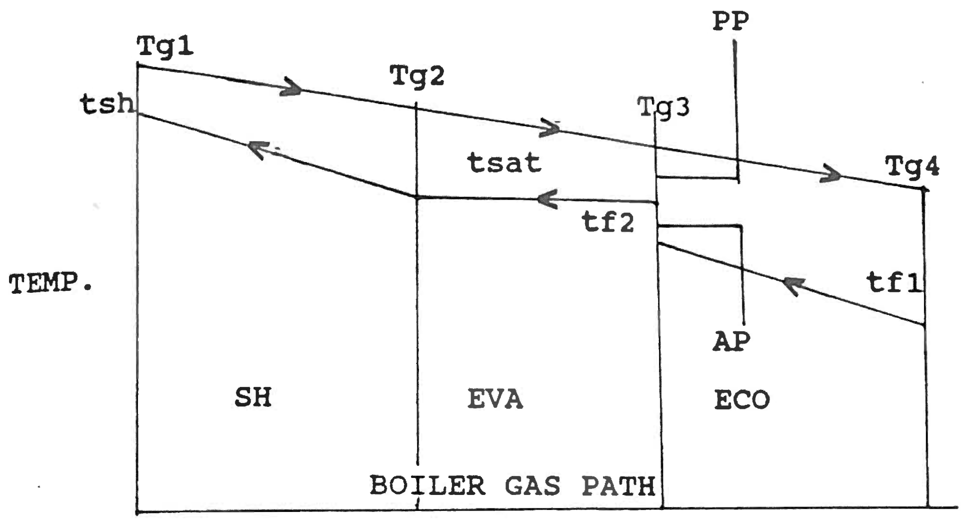
$$tf_1 = 240.0\ °F$$

Since the above two conditions are met, steam generation at the specified parameters is possible.

SUMMARY OF HRSG PERFORMANCE VALUES[1]

PARAMETER	HEAT TRANSFER SURFACE		
	S.H	**EVAP**	**ECON**
Gas inlet temp, °F	920	846	515
Gas Outlet temp, °F	846	515	400
Water/steam inlet, °F	493	475	240
Water/steam outlet, °F	757	493	475
Duty, million Btu/hr	11.08	46.04	15.85
Steam pressure, psig	600	624	624
Steam/water flow, 1000 lb/h	61.8	61.8	63.7
Pinch temperature, °F	--	--	22
Approach temperature, °F	--	--	18

[1]Based on exhaust flow of 525,000 lb/hr at 920 °F. Pressure drop in the economizer section neglected.



Performance Data

Tg1	(°F)	=	920
Tg2	(°F)	=	847
Tg3	(°F)	=	515
Tg4	(°F)	=	400
tsh	(°F)	=	757
tsat	(°F)	=	493
tf2	(°F)	=	475
tf1	(°F)	=	240
PP	(°F)	=	22
APP	(°F)	=	18

GAS FLOW (lb/s) = 145.83

STEAM FLOW (lb/s) = 17.22

Figure 3.3 Temperature Profile for the illustrative example

POWER GENERATION POSSIBLE IN STEAM TURBINE USING THE STEAM GENERATED IN HRSG

STEAM TURBINE DATA:

Steam inlet pressure (psia)	=	614.7
Steam inlet temperature (°F)	=	757
Steam exit pressure (psia)	=	1.45
Turbine Adiabatic Efficiency [AEFFC]	=	87.5 %
Turbine Mechanical Efficiency [MEFFC]	=	91.5 %
Turbine Generator Efficiency [GEFFC]	=	98.5 %

STEP 10

Calculate steam enthalpy and entropy at turbine inlet

Enthalpy at inlet (HEAT1)

Enthalpy at 614.7 psia and 757 °F = 1,383 Btu/lbm

Entropy at inlet (ENTR1)

Entropy at 614.7 psia and 757 °F = 1.61183 Btu/lbm-°F

STEP 11

Calculate steam enthalpy at turbine exit (ideal condition)

Enthalpy at exit (ideal condition) [IHEAT2] = 920 Btu/lbm

STEP 12

Calculate the actual enthalpy drop through the turbine (AED)

AED = (HEAT1 - IHEAT2) x AEFFC

AED = (1,383 - 920) Btu/lbm x 0.875
    = 405.13 Btu/lbm

STEP 13

Calculate actual enthalpy at exit (AHEAT2)

AHEAT2 = HEAT1 - AED

AHEAT2 = (1,383 - 405.13) Btu/lbm
       = 977.87 Btu/lbm

STEP 14

Calculate steam quality at exit

From Mollier Diagram, Moisture = 13%

STEP 15

Calculate the power generated at the generator terminals

POWER = AED x STGEN X (conv. factor) x (conv. factor) x MEFFC x GEFFC
      = 405.13 Btu/lbm x 61,797 lbm/hr x 0.45359 x 2.3259 x 0.915 x 0.985
      = 23,805 kW_e
      = 23.81 MW_e

The above example was run in "HGPRO" and the results are shown in the following section. It can be seen that the results obtained by "HGPRO" closely agree with the results in steps 1 through 15 in the example illustrated in section 3.3.

It should be noted that, while using the program no steam tables, Mollier diagrams, specific heat tables, or compressed water data were used.

SUMMARY

	DUTY (MBtu/hr)			STEAM GENERATED (lb/hr)	POWER GENERATED (MW)
	SH	EVA	ECO		
EXAMPLE	11.08	46.04	15.85	61.80	23.81
HGPRO	10.97	46.19	15.90	62.01	23.93
POWER[a] MAGAZINE	11.00	46.00	16.00	62.00	-----

[a]Performance results from the article Design/operating ideas by Steven Collins [20]

ANALYSIS OF THE ILLUSTRATIVE EXAMPLE USING "HGPRO"

INPUT MODULE

GAS TURBINE MODEL NUMBER	:	GE FRAME x
GAS TURBINE EXHAUST FLOW RATE (lbm/sec)	:	145.8334
GAS TURBINE EXHAUST TEMPERATURE (°F)	:	920

AVAILABLE OPTIONS
1. STEAM FOR INDUSTRIAL PROCESS (CO-GENERATION)
2. STEAM FOR ADDITIONAL ELECTRICAL POWER (COMBINED CYCLE)

CHOOSE ONE OF THE ABOVE OPTIONS FOR ANALYSIS

STEAM FOR ADDITIONAL ELECTRICAL POWER - (COMBINED CYCLE)

STEAM EXIT PRESSURE (PSIA)	:	1.45
TURBINE ADIABATIC EFFICIENCY (%)	:	87.5
TURBINE MECHANICAL EFFICIENCY (%)	:	91.5
ELECTRIC GENERATOR EFFICIENCY (%)	:	98.5

HAVE YOU ENTERED ALL THE VALUES CORRECTLY (Y/N) :

HEAT RECOVERY STEAM GENERATOR ANALYSIS

STEAM PRESSURE AT MSSV (lb/in²)	:	600
STEAM TEMPERATURE AT MSSV (°F)	:	757
FEED WATER TEMPERATURE TO HRSG (°F)	:	240
PINCH POINT (°F)	:	22
APPROACH POINT (°F)	:	18
VALVES + LINES + LINK LOSSES (lb/in²)	:	24

HAVE YOU ENTERED ALL THE VALUES CORRECTLY (Y/N) :

HGPRO - INPUT MODULES

HEAT RECOVERY STEAM GENERATOR (HRSG) ANALYSIS
GAS TURBINE MODEL NUMBER: GE FRAME x

GAS TURBINE EXHAUST FLOW RATE (lb/s)	=	145.83
GAS TURBINE EXHAUST TEMPERATURE (°F)	=	920.00
TEMP. OF EXHAUST GAS ENTERING SUPER HEATER (°F)	=	920.00
TEMP. OF EXHAUST GAS ENTERING EVAPORATOR (°F)	=	847.26
TEMP. OF EXHAUST GAS ENTERING ECONOMIZER (°F)	=	514.98
TEMPERATURE OF WATER ENTERING ECONOMIZER (°F)	=	240.00
TEMPERATURE OF STEAM AT MAIN STEAM STOP VALVE (°F)	=	757.00
PINCH POINT (°F)	=	22.00
APPROACH POINT (°F)	=	18.00
SUPERHEATER DUTY (MMBTU/hr)	=	10.97
EVAPORATOR DUTY (MMBTU/hr)	=	46.19
ECONOMIZER DUTY (MMBTU/hr)	=	15.90
STEAM FLOW AT MAIN STEAM STOP VALVE (x 1,000 lb/h)	=	62.01

PRESS ANY KEY TO CONTINUE

HGPRO - RESULTS AS ECHOED ON SCREEN

HGPRO VERSION - 1.0

DR. WAYNE C. TURNER, JORGE B. WONG, AND VISWANATHAN GANESH
SCHOOL OF INDUSTRIAL ENGINEERING & MANAGEMENT
OKLAHOMA STATE UNIVERSITY STILLWATER OK 74078

HEAT RECOVERY STEAM GENERATOR (HRSG) ANALYSIS
STEAM FOR ADDITIONAL POWER GENERATION

GAS TURBINE MODEL NUMBER: GE FRAME x

08-24-1992
12:45:08

GAS TURBINE

GAS TURBINE EXHAUST FLOW RATE (lb/s)	=	145.83
GAS TURBINE EXHAUST TEMPERATURE (°F)	=	920.00

HEAT RECOVERY STEAM GENERATOR

TEMP. OF EXHAUST GAS ENTERING SUPER HEATER (°F)	=	920.00
TEMP. OF EXHAUST GAS ENTERING EVAPORATOR (°F)	=	847.26
TEMP. OF EXHAUST GAS ENTERING ECONOMIZER (°F)	=	514.98
TEMPERATURE OF WATER ENTERING ECONOMIZER (°F)	=	240.00
SATURATION TEMPERATURE (°F)	=	492.98
PRESSURE LOSS IN VALVES, LINKS, & SH COIL (psig)	=	24.00
HRSG DRUM OPERATING PRESSURE (psig)	=	638.70
BOILER BLOW DOWN (x 1000 lbm/hr)	=	1.86
TEMPERATURE OF STEAM AT MAIN STEAM STOP VALVE (°F)	=	757.00
PRESSURE OF STEAM AT MAIN STEAM STOP VALVE (psig)	=	614.70
PINCH POINT (°F)	=	22.00
APPROACH POINT (°F)	=	18.00
SUPERHEATER DUTY (MMBTU/hr)	=	10.97
EVAPORATOR DUTY (MMBTU/hr)	=	46.19
ECONOMIZER DUTY (MMBTU/hr)	=	15.90
STEAM FLOW AT MAIN STEAM STOP VALVE (x 1,000 lb/h)	=	62.01

STEAM TURBINE GENERATOR

STEAM EXIT PRESSURE (psia)	=	1.45
TURBINE ADIABATIC EFFICIENCY (%)	=	87.50
TURBINE MECHANICAL EFFICIENCY (%)	=	91.50
ELECTRICAL GENERATOR EFFICIENCY (%)	=	98.50
ENTHALPY OF INLET STEAM (BTU/lbm)	=	1382.91
ENTROPY OF INLET STEAM (BTU/lbm-°F)	=	1.61
ENTHALPY AT EXIT-Ideal Conditions (BTU/lbm)	=	918.99
ENTHALPY AT EXIT-Actual Conditions (BTU/lbm)	=	976.98
ENTROPY AT EXIT-Actual Conditions (BTU/lbm-°F)	=	1.72
MOISTURE IN EXHAUST STEAM (%)	=	13.06
ELECTRICAL POWER (MWe)	=	23.93

"HGPRO" PROGRAM LISTING

```
100 REM -------------------------------------------------------------------
110 REM                       PROGRAM NAME: HGPRO
120 REM                          VERSION 1.0
130 REM       DR. WAYNE C. TURNER, JORGE B. WONG, and VISWANATHAN GANESH
140 REM              SCHOOL OF INDUSTRIAL ENGINEERING & MANAGEMENT
150 REM                     OKLAHOMA STATE UNIVERSITY
160 REM                      STILLWATER   OK 74078
170 REM                          SUMMER  1992
180 REM -------------------------------------------------------------------
190 REM   PROGRAM DESCRIPTION
200 REM
210 REM   THIS PROGRAM COMPUTES THE MAXIMUM STEAM THAT CAN BE
220 REM   GENERATED BASED ON THE GAS TURBINE EXHAUST QUANTITY
230 REM   & TEMPERATURE. ALSO, THE POWER GENERATION POTENTIAL
240 REM   USING THE  STEAM  GENERATED IN THE  HRSG CAN BE
250 REM   COMPUTED.
260 REM -------------------------------------------------------------------
270 REM
280 CLS : COLOR 7, 0
290 LOCATE 4, 6: PRINT STRING$(72, 220)
300 LOCATE 6, 33: PRINT "HGPRO  VERSION 1.0"
310 LOCATE 7, 22: PRINT "DR WAYNE C. TURNER, JORGE B. WONG & V. GANESH"
320 LOCATE 8, 19: PRINT "SCHOOL OF INDUSTRIAL ENGINEERING & MANAGEMENT"
330 LOCATE 9, 29: PRINT "OKLAHOMA STATE UNIVERSITY"
340 LOCATE 10, 32: PRINT "STILLWATER OK 74078"
350 LOCATE 11, 6: PRINT STRING$(72, 220)
360 LOCATE 13, 6: PRINT STRING$(72, 205)
```

```
370 LOCATE 14, 6: PRINT "HGPROfessional Calculates the Steam Quantity and
    Electrical Power"

380 LOCATE 15, 6: PRINT "that can be generated from a Heat Recovery Steam
    Generator Based on"

390 LOCATE 16, 6: PRINT "the Gas Turbine Exhaust Quantity and Temperature."

400 LOCATE 18, 6: PRINT "This Routine Selects the Optimum Pressure and
    Temperature Based on"

410 LOCATE 19, 6: PRINT "the Gas Turbine Exhaust Conditions or Allows User
    to Select these"

420 LOCATE 20, 6: PRINT "Parameters Based on the Process Requirements."

430 LOCATE 21, 6: PRINT STRING$(72, 205)

440 LOCATE 23, 30: COLOR 17, 15: PRINT "PRESS ANY KEY TO CONTINUE": COLOR 7, 0

450 P$ = INKEY$: IF P$ = "" THEN 450

460 CLS

470 REM --------------------------------------------------------------------

480 REM   INPUT MODULE PERTAINING TO INFORMATION ON GAS TURBINE PARAMETERS

490 REM --------------------------------------------------------------------

500 LOCATE 5, 6: PRINT STRING$(72, 205)

510 LOCATE 6, 36: PRINT "INPUT MODULE"

520 LOCATE 7, 6: PRINT STRING$(72, 205)

530 LOCATE 9, 8: INPUT "GAS TURBINE MODEL NUMBER                  : ", MODNO$

540 LOCATE 11, 8: INPUT "GAS TURBINE EXHAUST FLOW RATE (lbm/sec)  : ", EGTF

550 LOCATE 13, 8: INPUT "GAS TURBINE EXHAUST TEMPERATURE (½F)     : ", EGT1

560 LOCATE 15, 8: PRINT "AVAILABLE OPTIONS"

570 LOCATE 16, 8: PRINT " 1. STEAM FOR INDUSTRIAL PROCESS (CO-GENERATION)"

580 LOCATE 17, 8: PRINT " 2. STEAM FOR ADDITIONAL ELECTRICAL POWER (COMBINED
    CYCLE)"

590 LOCATE 19, 8: COLOR 17, 15: PRINT "CHOOSE ONE OF THE ABOVE OPTIONS FOR
    ANALYSIS" : COLOR 7, 0

600 LOCATE 21, 6: PRINT STRING$(72, 205)
```

```
610 A$ = INPUT$(1)

620 ANT$ = A$

630 LOCATE 19, 55: PRINT A$

640 IF A$ = "1" GOTO 920

650 IF A$ = "2" GOTO 690

660 BEEP

670 LOCATE 19, 55: PRINT " "

680 GOTO 590

690 CLS

700 REM

710 REM --------------------------------------------------------------------

720 REM   INPUT MODULE PERTAINING TO INFORMATION ON STEAM TURBINE GENERATOR

730 REM --------------------------------------------------------------------

740 LOCATE 3, 14: PRINT "STEAM FOR ADDITIONAL ELECTRICAL POWER - (COMBINED
     CYCLE)"

750 LOCATE 5, 6: PRINT STRING$(72, 220)

760 LOCATE 7, 8: INPUT "STEAM EXIT PRESSURE (PSIA)                   : ", EP

770 LOCATE 9, 8: INPUT "TURBINE ADIABATIC EFFICIENCY (%)             : ", AEFF

780 LOCATE 11, 8: INPUT "TURBINE MECHANICAL EFFICIENCY (%)           : ", MEFF

790 LOCATE 13, 8: INPUT "ELECTRIC GENERATOR EFFICIENCY (%)           : ", GEFF

800 LOCATE 15, 6: PRINT STRING$(72, 220)

810 LOCATE 18, 6: PRINT "HAVE YOU ENTERED ALL THE VALUES CORRECTLY (Y/N)  : "
     : YN1$ = INPUT$(1)

820 IF YN1$ = "N" OR YN1$ = "n" GOTO 690

830 IF YN1$ = "Y" OR YN1$ = "y" GOTO 850

840 BEEP: GOTO 800

850 AEFFC = AEFF / 100

860 MEFFC = MEFF / 100
```

```
870 GEFFC = GEFF / 100

880 CLS

890 REM --------------------------------------------------------------------

900 REM          INPUT MODULE PERTAINING TO INFORMATION ON HRSG

910 REM --------------------------------------------------------------------

920 CLS : LOCATE 5, 6: PRINT STRING$(72, 205)

930 LOCATE 6, 23: PRINT "HEAT RECOVERY STEAM GENERATOR ANALYSIS"

940 LOCATE 7, 6: PRINT STRING$(72, 205)

950 LOCATE 9, 12: INPUT "STEAM PRESSURE AT MSSV (lb/in»)        :  ", ESPMSSV

960 ESPMSSV = ESPMSSV + 14.69595

970 LOCATE 11, 12: INPUT "STEAM TEMPERATURE AT MSSV (½F)          :  ", ESTMSSV

980 LOCATE 13, 12: INPUT "FEED WATER TEMPERATURE TO HRSG (½F)     :  ", ETF1

990 LOCATE 15, 12: INPUT "PINCH POINT (½F)                        :  ", EPP

1000 LOCATE 17, 12: INPUT "APPROACH POINT (½F)                     :  ", EAPP

1010 LOCATE 19, 12: INPUT "VALVES + LINES + LINK LOSSES (lb/in»)  :  ", ELOSS

1020 LOCATE 21, 6: PRINT STRING$(72, 205)

1030 LOCATE 23, 12: PRINT "HAVE YOU ENTERED ALL THE VALUES CORRECTLY (Y/N) : "
     : AA$ = INPUT$(1)

1040 IF AA$ = "n" OR AA$ = "N" GOTO 880

1050 IF AA$ = "y" OR AA$ = "Y" GOTO 1070

1060 BEEP: GOTO 1030

1070 P2 = ESPMSSV

1080 X = .43429448# * LOG(P2)

1090 X4 = X * X * X * X

1100 TSL = 101.74419# + (77.052576# + (11.951549# + 2.0562054# * X) * X) * X
      + (.42070502# + (-6.841098700000001D-02 + .0625368 * X) * X) * X4
        - .0065948781# * X * X * X * X4

1120 IF TSL > ESTMSSV THEN 1130 ELSE 1250

1130 CLS
```

```
1140 LOCATE 6, 20: PRINT "         -------------------------- "

1150 LOCATE 7, 20: PRINT "                    ERROR!          "

1160 LOCATE 8, 20: PRINT "         -------------------------- "

1170 LOCATE 10, 6: PRINT STRING$(72, 254)

1180 LOCATE 12, 10: PRINT "THE STEAM TEMPERATURE AT MSSV ("; ESTMSSV; "½F)
     IS LESS THAN THE"

1190 LOCATE 13, 10: PRINT "SATURATION TEMPERATURE ("; TSL; "½F)."

1200 LOCATE 14, 10: PRINT "PLEASE REENTER THE APPROPRIATE VALUES."

1210 LOCATE 16, 6: PRINT STRING$(72, 254)

1220 LOCATE 19, 21: COLOR 17, 15: PRINT "PLEASE REENTER DATA - PRESS ANY
     KEY TO RETURN": COLOR 7, 0

1230 P$ = INKEY$: IF P$ = "" THEN 1230

1240 GOTO 880

1250 CLS

1260 EDOP = ESPMSSV + ELOSS

1270 P2 = EDOP

1280 X = .43429448# * LOG(P2)

1290 X4 = X * X * X * X

1300 TSL = 101.74419# + (77.052576# + (11.951549# + 2.0562054# * X) * X) * X
      + (.42070502# + (-6.841098700000001D-02 + .0625368 * X) * X) * X4 -
     .0065948781# * X * X * X * X4 1310 ETSH = ESTMSSV

1320 ETSAT = TSL

1330 ETF2 = ETSAT - EAPP

1340 EGT3 = ETSAT + EPP

1350 REM -----------------------------------------------------------------

1360 REM                HEAT AVAILABLE FOR STEAM GENERATION

1370 REM -----------------------------------------------------------------

1380 IF EGT1 > 1000 THEN CPG1 = .264 + .0000325 * (EGT1 - 400) ELSE
     CPG1 = .258 + .00003 * (EGT1 - 400)
```

```
1390 IF EGT3 > 1000 THEN CPG3 = .264 + .0000325 * (EGT3 - 400) ELSE
      CPG3 = .258 + .00003 * (EGT3 - 400)

1400 HG1 = EGT1 * CPG1

1410 HG3 = EGT3 * CPG3

1420 QG13 = .93 * EGTF * 3600 * (HG1 - HG3)

1430 EPSH = EDOP + ELOSS

1440 REM -------------------------------------------------------------------

1450 REM             ENTHALPY REQUIRED TO CONVERT WATER TO STEAM

1460 REM -------------------------------------------------------------------

1470 T1 = ESTMSSV

1480 P1 = EPSH

1490 T2 = 255.38 + T1 / 1.8

1500 P2 = P1 / 14.6959

1510 B1 = (2641.62 * 10 ^ (80870! / (T2 * T2))) / T2

1520 B0 = 1.89 - B1

1530 B2 = 82.546

1540 B3 = 162460! / T2

1550 B4 = .21828 * T2

1560 B5 = 126970! / T2

1570 F0 = 1.89 - B1 * (372420! / (T2 * T2) + 2!)

1580 B6 = B0 * B3 - 2! * F0 * (B2 - B3)

1590 B7 = 2! * F0 * (B4 - B5) - B0 * B5

1600 B8 = .43429448# * LOG(T2)

1610 F = 775.596 + (.63296 + 1.62467E-04 * T2) * T2 + 47.3635 * B8

1620 B9 = B0 * P2 * P2 / (2! * T2 * T2)

1630 HTP = F + .043557 * (F0 * P2 + B9 * (B0 * (B2 - B3 + 2! *
      B7 * B9) - B6))

1640 REM
```

```
1650 T = ETF2: P = EDOP

1660 T3 = T * T * T

1670 T4 = T * T3

1680 A0 = .75623 + (-.01446 + 9.850369E-05 * T) * T + (-2.8685E-07 +
      2.87767E-10 * T) * T3

1690 A1 = 3.14899E-03 + (-4.867E-06 - 2.1607E-09 * T) * T + (4.07626E-11
      - 9.30412E-14 * T) * T3

1700 A2 = -3.1788E-08 + (2.80539E-11 + 1.75513E-12 * T) * T + (-7.4798E-15
      + 9.90718E-18 * T) * T3

1710 HF = -32.46 + (1.02493 + (-4.1498E-04 + 3.07768E-06 * T) * T) * T
      + (-1.2602E-08 + (3.06581E-11 - 3.834E-14 * T) * T) * T4 + 1.9907E-17
      * T * T * T * T4

1720 HCL = A0 + (A1 + A2 * P) * P + HF

1730 REM --------------------------------------------------------------------

1740 REM                    STEAM GENERATION POTENTIAL

1750 REM --------------------------------------------------------------------

1760 STGEN = QG13 / (HTP - HCL)

1770 REM --------------------------------------------------------------------

1780 REM                        MODULE TO FIND ETG2

1790 REM --------------------------------------------------------------------

1800 T1 = ETSAT

1810 TK = (T1 - 32!) / 1.8 + 273.16

1820 X = 647.27 - TK

1830 Y = X * (3.2438 + (.0058683 + 1.17024E-08 * X * X) * X) / (TK * (1!
      + 2.18785E-03 * X))

1840 P = 14.6959 * 218.167 / (10! ^ Y)

1850 X = LOG(P) / LOG(10!)

1860 HGT = 1105.94 + (32.756807# + (4.6198474# + (.20672996# + (-.5411693 +
      (.49241362# - .17884885# * X) * X) * X) * X) * X) * X

1870 REM

1880 QSH = STGEN * (HTP - HGT)
```

```
1890 REM ------------------------------------------------------------------
1900 REM                    ENTHALPY DROP ON GAS SIDE
1910 REM ------------------------------------------------------------------
1920 ENTHDRO = QSH / (.96 * EGTF * 3600)
1930 ENTHTG2 = HG1 - ENTHDRO
1940 FOR TEMPCOMP = 100 TO 1000 STEP .5
1950 CPGCOMP = .258 + .00003 * (TEMPCOMP - 400)
1960 ENTCOMP = TEMPCOMP * CPGCOMP
1970 IF ABS(ENTHTG2 - ENTCOMP) <= .1 GOTO 1990
1980 NEXT TEMPCOMP
1990 EGT2 = ENTHTG2 / CPGCOMP
2000 REM ------------------------------------------------------------------
2010 REM                         EVAPORATOR DUTY
2020 REM ------------------------------------------------------------------
2030 QEVA = STGEN * (HGT - HCL)
2040 REM ------------------------------------------------------------------
2050 REM                         ECONOMIZER DUTY
2060 REM ------------------------------------------------------------------
2070 WATFLO = 1.03 * STGEN
2080 BLOWDOWN = WATFLO - STGEN
2090 T = ETF1: P = EDOP + 10
2100 T3 = T * T * T
2110 T4 = T * T3
2120 A0 = .75623 + (-.01446 + 9.850369E-05 * T) * T + (-2.8685E-07 +
      2.87767E-10 * T) * T3
2130 A1 = 3.14899E-03 + (-4.867E-06 - 2.1607E-09 * T) * T + (4.07626E-11
      - 9.30412E-14 * T) * T3
2140 A2 = -3.1788E-08 + (2.80539E-11 + 1.75513E-12 * T) * T + (-7.4798E-15
      + 9.90718E-18 * T) * T3
```

```
2150 HF = -32.46 + (1.02493 + (-4.1498E-04 + 3.07768E-06 * T) * T) * T
     + (-1.2602E-08 + (3.06581E-11 - 3.834E-14 * T) * T) * T4
     + 1.9907E-17 * T * T * T * T4

2160 HCL2 = A0 + (A1 + A2 * P) * P + HF

2170 QECO = WATFLO * (HCL - HCL2)

2180 REM -------------------------------------------------------------------

2190 REM                 GAS SIDE ENTHALPY DROP IN ECO SECTION

2200 REM -------------------------------------------------------------------

2210 ENTHDRO = QECO / (.96 * EGTF * 3600)

2220 HG4 = HG3 - ENTHDRO

2230 FOR TEMPCOMP = 100 TO 1000 STEP .5

2240 CPGCOMP = .258 + .00003 * (TEMPCOMP - 400)

2250 ENTCOMP = TEMPCOMP * CPGCOMP

2260 IF ABS(HG4 - ENTCOMP) <= .1 GOTO 2280

2270 NEXT TEMPCOMP

2280 EGT4 = HG4 / CPGCOMP

2290 REM -------------------------------------------------------------------

2300 REM                      CHECK FOR PROPER PINCH POINT

2310 REM -------------------------------------------------------------------

2320 IF EGT3 < ETSAT OR EGT4 < ETF1 THEN 2330 ELSE 2490

2330 LOCATE 5, 20: PRINT "         ------------------------- "

2340 LOCATE 6, 20: PRINT "                   ERROR!          "

2350 LOCATE 7, 20: PRINT "         ------------------------- "

2360 LOCATE 10, 6: PRINT STRING$(72, 254)

2370 LOCATE 11, 10: PRINT "Tg3 = "; EGT3; " Tg4 = "; EGT4

2380 LOCATE 12, 10: PRINT "tsat= "; ETSAT; " tw1 = "; ETF1

2390 LOCATE 13, 10: PRINT "PP = "; EPP; " AP = "; EAPP

2400 LOCATE 14, 6: PRINT STRING$(72, 205)
```

```
2410 LOCATE 15, 10: PRINT "FOR STEAM GENERATION TO OCCUR  Tg3 > tsat
     & tg4 > twl."
2420 LOCATE 16, 10: PRINT "ONE OR BOTH OF THE ABOVE CONDITIONS IS NOT MET WITH"
2430 LOCATE 17, 10: PRINT "THE PINCH POINT CHOSEN. PLEASE CHOOSE A DIFFERENT"
2440 LOCATE 18, 10: PRINT "PINCH POINT."
2450 LOCATE 19, 6: PRINT STRING$(72, 254)
2460 LOCATE 22, 31: COLOR 17, 15: PRINT "PRESS ANY KEY TO RETURN": COLOR 7, 0
2470 P$ = INKEY$: IF P$ = "" THEN 2470
2480 GOTO 880
2490 IF ANT$ = "1" GOTO 4240
2500 IF ANT$ = "2" GOTO 2510
2510 REM --------------------------------------------------------------------
2520 REM            STEAM ENTHALPY & ENTROPY AT TURBINE INLET
2530 REM --------------------------------------------------------------------
2540 T1 = ESTMSSV
2550 P1 = ESPMSSV
2560 GOSUB 3730
2570 HEAT1 = HTP
2580 GOSUB 3900
2590 ENTR1 = STP
2600 REM --------------------------------------------------------------------
2610 REM                    STEAM ENTHALPY AT TURBINE EXIT
2620 REM --------------------------------------------------------------------
2630 P = EP
2640 S = ENTR1
2650 GOSUB 3100
2660 IHEAT2 = HPS
```

```
2670 REM --------------------------------------------------------------------
2680 REM                    ACTUAL ENTHALPY DROP THROUGH THE TURBINE
2690 REM --------------------------------------------------------------------
2700 IED = HEAT1 - IHEAT2
2710 AED = AEFFC * (HEAT1 - IHEAT2)
2720 AHEA2 = HEAT1 - AED
2730 REM --------------------------------------------------------------------
2740 REM                      POWER GENERATED AT GENERATOR TERMINAL
2750 REM --------------------------------------------------------------------
2760 POWER = AED * (STGEN) * .45359 * 2.3259 * MEFFC * GEFFC / 1000
2770 REM --------------------------------------------------------------------
2780 REM                          STEAM QUALITY AT TURBINE EXIT
2790 REM --------------------------------------------------------------------
2800 P = EP
2810 GOSUB 3650
2820 TOTHE2 = HFP
2830 GOSUB 4080
2840 LIQHE2 = HGP
2850 LAT2 = TOTHE2 - LIQHE2
2860 QUAL = (AHEA2 - LIQHE2) / LAT2
2870 REM --------------------------------------------------------------------
2880 REM                         ACTUAL ENTROPY AT TURBINE EXIT
2890 REM --------------------------------------------------------------------
2900 GOSUB 3000
2910 TOTEN2 = SGP
2920 GOSUB 4120
2930 LIQEN2 = SFP
```

```
2940 LATEN2 = TOTEN2 - LIQEN2
2950 OUTENT = LIQEN2 + ((1 - QUAL) * LATEN2)
2960 GOTO 4230
2970 REM
2980 REM SUBROUTINES TO COMPUTE STEAM PROPERTIES
2990 REM
3000   REM  FUNCTION SGP(P)
3010   IF P <= 100 THEN GOTO 3070
3020   IF P > 2000 THEN GOTO 3050
3030   SGP = 2.2411 / (P ^ .07007)
3040   RETURN
3050   SGP = 5.66316 / (P ^ .19494)
3060   RETURN
3070   SGP = 1.98473 / (P ^ .04589)
3080   RETURN
3090   REM
3100   REM  FUNCTION HPS(P,S)
3110   IF P > 100! THEN GOTO 3140
3120   SG = 1.9847258# / (P ^ 4.589071E-02)
3130   GOTO 3180
3140   IF P > 2000! THEN GOTO 3170
3150   SG = 2.2410983# / (P ^ .070069)
3160   GOTO 3180
3170   SG = 5.6631597# / (P ^ .1949355)
3180   IF SG >= S THEN GOTO 3470
3190   X = .43429448# * LOG(P)
3200   X4 = X * X * X * X
```

```
3210    IF P > 10! THEN GOTO 3290

3220    S0 = 2.150098+(-.25438439#+(2.17448E-04-9.3986E-04*X)*X)*X

3230    A0 = 1223.2933#+(-.5778129400000001#+(.2303143-1.0434265#*X)*X)*X

3240    A1 = 820.09617#+(-1.9634176#+(2.6069465#-.76847051#*X)*X)*X

3250    A2 = 895.12074#+(-10.468214#+(7.0858389#-10.321004#*X)*X)*X

3260    A3 = 547.70336#+(195.11068#+(-313.48831#+166.94769#*X)*X)*X

3270    A4 = 0!

3280    GOTO 3440

3290    IF P > 450! THEN GOTO 3380

3300    S0 = 2.3335568# + (-.3201163 + (.086914914#
          - .056646879# * X) * X) * X

3310    S0 = S0 + (.018338725# - 2.447789E-03 * X) * X4

3320    A0 = 1357.2272# + (73.791077# + (-75.92468100000001# + 34.275666# *
          X) * X) * X - 6.0270154# * X4

3330    A1 = 1144.6178# + (33.297322# + (-26.451758# + 8.9579684# * X)
          * X) * X - 1.0968016# * X4

3340    A2 = 993.78383# + (521.1335 + (-506.58014# + 220.41684# * X) * X) * X
          - 37.982498# * X4

3350    A3 = 1424.0878# + (-1663.6047# + (1345.659 - 489.18341# * X) * X) * X
          + 73.075686# * X4

3360    A4 = 3431.7851# + (-7341.2575# + (5997.1054# - 2208.4202# * X)
          * X) * X + 297.74553# * X4

3370    GOTO 3440

3380    S0 = 1.7066779# + (.54400879# + (-.37780533# + 7.709329099999999D-02
          * X) * X) * X - .0054871968# * X4

3390    A0 = 1400!

3400    A1 = 742.2428 + (661.0354 + (-321.27928# + 53.456926#*X)*X)*X

3410    A2 = -3491.438+(4615.4327#+(-1470.6537#+145.94655#*X)*X)*X

3420    A3 = 34807.748#+(-35596.564#+(12288.438#-1388.0814#*X)*X)*X

3430    A4 = 0!

3440    A5 = S - S0
```

```
3450  HPS = A0 + (A1 + (A2 + (A3 + A4 * A5) * A5) * A5) * A5

3460  RETURN

3470  X = .43429448# * LOG(P)

3480  X4 = X * X * X * X

3490  A0 = -4.7169141# + (-10.049146# + (-7.0532835# - 1.9473822# * X) * X)
        * X + (.1175487 - .25473452# * X) * X4

3500  A1 = 561.46162# + (76.93328 + (12.117678# + 2.1291364# * X) * X) * X
        + (.12850077# + .14437713# * X) * X4

3510  HPS = A0 + A1 * S

3520  RETURN

3530  REM

3540  REM  FUNCTION TSL(P2)

3550  X = .43429448# * LOG(P2)

3560  X4 = X * X * X * X

3570  TSL = 101.74419# + (77.052576# + (11.951549# + 2.0562054# * X) * X)
        * X + (.42070502# + (-6.841098700000001D-02 + .0625368 * X) * X) * X4
        - .0065948781# * X * X * X * X4

3580  RETURN

3590  REM

3600  REM  FUNCTION HFT(T)

3610  T4 = T * T * T * T

3620  HFT = -32.4599 + (1.02493 + (-4.1498E-04 + 3.0777E-06 * T) * T) * T
        + (-1.2603E-08 + (3.06581E-11 - 3.8341E-14 * T) * T) * T4 + 1.9907E-17
        * T * T * T * T4

3630  RETURN

3640  REM

3650  REM  FUNCTION HFP(P)

3660  X = .43429448# * LOG(P)

3670  X4 = X * X * X * X
```

```
3680   T = 101.74419# + (77.052576# + (11.951549# + 2.0562054# * X) * X) * X
         + (.42070502# + (-6.841098700000001D-02 + .0625368 * X) * X) * X4
         - .0065948781# * X * X * X * X4

3690   T4 = T * T * T * T

3700   HFP = -32.4599 + (1.02494 + (-4.14977E-04 + 3.0777E-06 * T) * T) * T
         + (-1.26029E-08 + (3.0658E-11 - 3.8341E-14 * T) * T) * T4
         + 1.99068E-17 * T * T * T * T4

3710   RETURN

3720   REM

3730   REM  FUNCTION HTP(T1,P1)

3740   T2 = 255.38 + T1 / 1.8

3750   P2 = P1 / 14.6959

3760   B1 = (2641.62 * 10 ^ (80870! / (T2 * T2))) / T2

3770   B0 = 1.89 - B1

3780   B2 = 82.546

3790   B3 = 162460! / T2

3800   B4 = .21828 * T2

3810   B5 = 126970! / T2

3820   F0 = 1.89 - B1 * (372420! / (T2 * T2) + 2!)

3830   B6 = B0 * B3 - 2! * F0 * (B2 - B3)

3840   B7 = 2! * F0 * (B4 - B5) - B0 * B5

3850   B8 = .43429448# * LOG(T2)

3860   F = 775.596 + (.63296 + 1.62467E-04 * T2) * T2 + 47.3635 * B8

3870   B9 = B0 * P2 * P2 / (2! * T2 * T2)

3880   HTP = F + .043557 * (F0 * P2 + B9 *(B0*(B2-B3+2!*B7*B9)-B6))

3890   RETURN

3900   REM  FUNCTION STP(T1,P1)

3910   T = 255.38 + T1 / 1.8

3920   P = P1 / 14.6959
```

```
3930  B1 = (2641.62 * 10 ^ (80870! / (T * T))) / T
3940  B0 = 1.89 - B1
3950  B2 = 82.546
3960  B3 = 162460! / T
3970  B4 = .21828 * T
3980  B5 = 126970! / T
3990  F0 = 1.89 - B1 * (372420! / (T * T) + 2!)
4000  B6 = B0 * B3 - 2! * F0 * (B2 - B3)
4010  B7 = 2! * F0 * (B4 - B5) - B0 * B5
4020  B8 = .43429448# * LOG(T)
4030  B9 = B0 * P * P / (2! * T * T)
4040  BETA = ((B0 - F0) * P + B9 * (B6 + B9 * B0 * (B0 * (B4 - B5) -
        2! * B7))) / T
4050  STP = .809691 * B8 - .253801 * .43429448# * LOG(P) + 1.8052E-04 * T
        - 11.4276 / T - .355579 - .0241983 * BETA
4060  RETURN
4070  REM
4080  REM  FUNCTION HGP(P)
4090  X = LOG(P) / LOG(10!)
4100  HGP = 1105.9387# + (32.756807# + (4.6198474# + (.20672996# +
        (-.5411693#+(.49241362#-.17884885# * X) * X) * X) * X) * X) * X
4110  RETURN
4120  REM  FUNCTION SFP(P)
4130  REM  THIS FUNCTION REQUIRES TSL(P)
4140  P2 = P
4150  GOSUB 3540
4160  TSLPP = TSL
4170  TB = (TSLPP - 360!) / 3100!
```

```
4180   SFP = .515755 + (3.96796 - (4.59799 - (34.2517 - (60.7233 + (367.036
         - (12035.9 + 123466! * TB) * TB) * TB) * TB) * TB) * TB) * TB

4190   RETURN

4200 REM -------------------------------------------------------------------

4210 REM                        RESULTS ECHOED ON SCREEN

4220 REM -------------------------------------------------------------------

4230 CLS

4240 KEY OFF: CLS

4250 SCREEN 2

4260 LOCATE 1, 27: PRINT "HRSG - TEMPERATURE PROFILE"

4270 LOCATE 2, 27: PRINT STRING$(26, "-")

4280 LINE (100, 40)-(100, 155)

4290 LINE (100, 155)-(412, 155)

4300 LINE (204, 45)-(204, 155)

4310 LINE (308, 45)-(308, 155)

4320 LINE (412, 45)-(412, 155)

4330 LINE (100, 47)-(412, 75)

4340 LINE (100, 55)-(204, 75)

4350 LINE (204, 75)-(308, 75)

4360 LINE (308, 85)-(412, 100)

4370 LOCATE 18, 19: PRINT "SH"

4380 LOCATE 18, 31: PRINT "EVA"

4390 LOCATE 18, 44: PRINT "ECO"

4400 LOCATE 6, 14: PRINT "Tg1"

4410 LOCATE 7, 27: PRINT "Tg2"

4420 LOCATE 8, 40: PRINT "Tg3"

4430 LOCATE 10, 53: PRINT "Tg4"

4440 LOCATE 10, 31: PRINT "tsat"
```

```
4450 LOCATE 8, 11: PRINT "tsh"
4460 LOCATE 12, 37: PRINT "tf2"
4470 LOCATE 14, 52: PRINT "tf1"
4480 LINE (348, 40)-(348, 74)
4490 LINE (348, 74)-(308, 74)
4500 LOCATE 5, 44: PRINT "PP"
4510 LINE (348, 81)-(308, 81)
4520 LINE (348, 81)-(348, 117)
4530 LOCATE 16, 44: PRINT "AP"
4540 LINE (450, 14)-(450, 180)
4550 LOCATE 3, 59: PRINT "Performance Data "
4560 LOCATE 5, 59: PRINT "Tg1  (½F) = "
4570 LOCATE 5, 71: PRINT USING "###"; EGT1
4580 LOCATE 6, 59: PRINT "Tg2  (½F) = "
4590 LOCATE 6, 71: PRINT USING "###"; EGT2
4600 LOCATE 7, 59: PRINT "Tg3  (½F) = "
4610 LOCATE 7, 71: PRINT USING "###"; EGT3
4620 LOCATE 8, 59: PRINT "Tg4  (½F) = ";
4630 LOCATE 8, 71: PRINT USING "###"; EGT4
4640 LOCATE 10, 59: PRINT "tsh  (½F) = "
4650 LOCATE 10, 71: PRINT USING "###"; ETSH
4660 LOCATE 11, 59: PRINT "tsat (½F) = "
4670 LOCATE 11, 71: PRINT USING "###"; ETSAT
4680 LOCATE 12, 59: PRINT "tf2  (½F) = "
4690 LOCATE 12, 71: PRINT USING "###"; ETF2
4700 LOCATE 13, 59: PRINT "tf1  (½F) = "
4710 LOCATE 13, 71: PRINT USING "###"; ETF1
```

```
4720 LOCATE 15, 59: PRINT "PP   (½F) = "; EPP
4730 LOCATE 16, 59: PRINT "APP  (½F) = "; EAPP
4740 LOCATE 18, 59: PRINT "GAS FLOW (lb/s)"
4750 LOCATE 19, 59: PRINT " ="
4760 LOCATE 19, 62: PRINT USING "###.##"; EGTF
4770 LOCATE 21, 59: PRINT "STEAM FLOW (lb/s)"
4780 LOCATE 22, 59: PRINT " ="
4790 LOCATE 22, 62: PRINT USING "###.##"; STGEN / 3600
4800 LINE (610, 14)-(610, 180)
4810 LINE (450, 14)-(610, 14)
4820 LINE (450, 25)-(610, 25)
4830 LINE (450, 180)-(610, 180)
4840 LOCATE 14, 7: PRINT "TEMP."
4850 LOCATE 21, 25: PRINT " BOILER GAS PATH"
4860 FOR I = 1 TO 90: LOCATE 23, 20: PRINT "PRESS ANY KEY FOR SUMMARY": NEXT I
4870 FOR J = 1 TO 25: LOCATE 23, 20: PRINT "                         ": NEXT J
4880 P$ = INKEY$: IF P$ = "" THEN 4860
4890 SCREEN 0
4900 CLS
4910 REM SCREEN OUTPUT ROUTINE
4920 LOCATE 1, 15: PRINT "  HEAT RECOVERY STEAM GENERATOR (HRSG) ANALYSIS"
4930 LOCATE 2, 15: PRINT "  GAS TURBINE MODEL NUMBER: "; MODNO$
4940 LOCATE 4, 8: PRINT STRING$(68, 205)
4950 PRINT
4960 PRINT "         GAS TURBINE EXHAUST FLOW RATE (lb/s)               = "
     : LOCATE 6, 68: PRINT USING "###.##"; EGTF
4970 PRINT "         GAS TURBINE EXHAUST TEMPERATURE (½F)               = "
     : LOCATE 7, 67: PRINT USING "####.##"; EGT1
```

```
4980 PRINT "          TEMP. OF EXHAUST GAS ENTERING SUPER HEATER (½F)    = "
      : LOCATE 8, 67: PRINT USING "####.##"; EGT1

4990 PRINT "          TEMP. OF EXHAUST GAS ENTERING EVAPORATOR (½F)      = "
      : LOCATE 9, 67: PRINT USING "####.##"; EGT2

5000 PRINT "          TEMP. OF EXHAUST GAS ENTERING ECONOMIZER (½F)      = "
      : LOCATE 10, 67: PRINT USING "####.##"; EGT3

5010 PRINT "          TEMPERATURE OF WATER ENTERING ECONOMIZER (½F)      = "
      : LOCATE 11, 68: PRINT USING "###.##"; ETF1

5020 PRINT "          TEMPERATURE OF STEAM AT MAIN STEAM STOP VALVE (½F) = "
      : LOCATE 12, 68: PRINT USING "###.##"; ESTMSSV

5030 PRINT "          PINCH POINT (½F)                                   = "
      : LOCATE 13, 69: PRINT USING "##.##"; EPP

5040 PRINT "          APPROACH POINT (½F)                                = "
      : LOCATE 14, 69: PRINT USING "##.##"; EAPP

5050 PRINT " "

5060 PRINT "          SUPERHEATER DUTY (MMBTU/hr)                        = "
      : LOCATE 16, 68: PRINT USING "###.##"; QSH / 1000000!

5070 PRINT "          EVAPORATOR DUTY (MMBTU/hr)                         = "
      : LOCATE 17, 68: PRINT USING "###.##"; QEVA / 1000000!

5080 PRINT "          ECONOMIZER DUTY (MMBTU/hr)                         = "
      : LOCATE 18, 68: PRINT USING "###.##"; QECO / 1000000!

5090 PRINT ""

5100 PRINT "          STEAM FLOW AT MAIN STEAM STOP VALVE (x 1,000 lb/h) = "
      : LOCATE 20, 68: PRINT USING "###.##"; STGEN / 1000

5110 LOCATE 21, 8: PRINT STRING$(68, 205)

5120 IF ANT$ = "2" GOTO 5740

5130 LOCATE 23, 18: COLOR 17, 15: PRINT " WANT A HARD COPY OF THE
      RESULTS (Y/N):  ": COLOR 7, 0

5140 A$ = INPUT$(1): LOCATE 23, 58: PRINT A$

5150 IF A$ = "y" OR A$ = "Y" THEN 5190

5160 IF A$ = "n" OR A$ = "N" THEN 6720

5170 BEEP: LOCATE 23, 58: PRINT " ": GOTO 5130
```

```
5180 REM ------------------------------------------------------------
5190 REM                    ROUTINE FOR HARD COPY
5200 REM ------------------------------------------------------------
5210 LPRINT ""
5220 LPRINT ""
5230 LPRINT ""
5240 LPRINT ""
5250 LPRINT "                        HGPRO  VERSION - 1.0"
5260 LPRINT "    DR. WAYNE C. TURNER, JORGE B. WONG, AND VISWANATHAN GANESH"
5270 LPRINT "          SCHOOL OF INDUSTRIAL ENGINEERING & MANAGEMENT"
5280 LPRINT "          OKLAHOMA STATE UNIVERSITY  STILLWATER  OK 74078"
5290 LPRINT " "
5300 LPRINT "           HEAT RECOVERY STEAM GENERATOR (HRSG) ANALYSIS"
5310 LPRINT "            STEAM FOR INDUSTRIAL PROCESS (COGENERATION)"
5320 LPRINT ""
5330 LPRINT "                GAS TURBINE MODEL NUMBER: "; MODNO$
5340 LPRINT " "
5350 LPRINT "                                                   "; DATE$
5360 LPRINT "                                                   "; TIME$
5370 LPRINT ""
5380 LPRINT "        -------------------------------------------------------"
5390 LPRINT ""
5400 LPRINT "           GAS TURBINE EXHAUST FLOW RATE (lb/s)             = ";
      : LPRINT USING "####.##"; EGTF
5410 LPRINT "           GAS TURBINE EXHAUST TEMPERATURE (½F)             = ";
      : LPRINT USING "####.##"; EGT1
5420 LPRINT ""
5430 LPRINT
```

```
5440 LPRINT "              TEMP. OF EXHAUST GAS ENTERING SUPER HEATER (½F)     = ";
     : LPRINT USING "####.##"; EGT1

5450 LPRINT "              TEMP. OF EXHAUST GAS ENTERING EVAPORATOR (½F)       = ";
     : LPRINT USING "####.##"; EGT2

5460 LPRINT "              TEMP. OF EXHAUST GAS ENTERING ECONOMIZER (½F)       = ";
     : LPRINT USING "####.##"; EGT3

5470 LPRINT ""

5480 LPRINT ""

5490 LPRINT "              TEMPERATURE OF WATER ENTERING ECONOMIZER (½F)       = ";
     : LPRINT USING "####.##"; ETF1

5500 LPRINT "              SATURATION TEMPERATURE (½F)                         = ";
     : LPRINT USING "####.##"; ETSAT

5510 LPRINT "              PRESSURE LOSS IN VALVES, LINKS, & SH COIL (psig)    = ";
     : LPRINT USING "####.##"; ELOSS

5520 LPRINT "              HRSG DRUM OPERATING PRESSURE (psig)                 = ";
     : LPRINT USING "####.##"; EDOP - 14.7

5530 LPRINT "              BOILER BLOW DOWN (x 1000 lbm/hr)                    = ";
     : LPRINT USING "####.##"; BLOWDOWN / 1000

5540 LPRINT ""

5550 LPRINT ""

5560 LPRINT "              TEMPERATURE OF STEAM AT MAIN STEAM STOP VALVE (½F) = ";
     : LPRINT USING "####.##"; ESTMSSV

5570 LPRINT "              PRESSURE OF STEAM AT MAIN STEAM STOP VALVE (psig)  = ";
     : LPRINT USING "####.##"; ESPMSSV - 14.7

5580 LPRINT ""

5590 LPRINT ""

5600 LPRINT "              PINCH POINT (½F)                                    = ";
     : LPRINT USING "####.##"; EPP

5610 LPRINT "              APPROACH POINT (½F)                                 = ";
     : LPRINT USING "####.##"; EAPP

5620 LPRINT ""

5630 LPRINT ""

5640 LPRINT "              SUPERHEATER DUTY (MMBTU/hr)                         = ";
     : LPRINT USING "####.##"; QSH / 1000000!
```

```
5650 LPRINT "             EVAPORATOR DUTY (MMBTU/hr)                       = ";
      : LPRINT USING "####.##"; QEVA / 1000000!

5660 LPRINT "             ECONOMIZER DUTY (MMBTU/hr)                       = ";
      : LPRINT USING "####.##"; QECO / 1000000!

5670 LPRINT ""

5680 LPRINT ""

5690 LPRINT "             STEAM FLOW AT MAIN STEAM STOP VALVE (x 1,000 lb/h) = ";
      : LPRINT USING "####.##"; STGEN / 1000

5700 LPRINT

5710 LPRINT "          --------------------------------------------------------"

5720 GOTO 6720

5730 REM

5740 LOCATE 23, 29: COLOR 17, 15: PRINT "PRESS ANY KEY TO CONTINUE": COLOR 7, 0

5750 P$ = INKEY$: IF P$ = "" THEN 5750

5760 CLS

5770 REM --------------------------------------------------------------------

5780 REM                 INPUT DATA AND OUTPUT RESULTS ECHOED ON SCREEN

5790 REM --------------------------------------------------------------------

5800   PRINT "                            TURBINE - GENERATOR DATA"

5810   PRINT "                            ------------------------"

5820   PRINT

5830   PRINT "           STEAM INLET PRESSURE (PSIA)              = "; ESPMSSV

5840   PRINT "           STEAM INLET TEMPERATURE (½F)             = "; ESTMSSV

5850   PRINT "           STEAM EXIT PRESSURE (PSIA)               = "; EP

5860   PRINT "           STEAM MASS FLOW RATE (lb/sec)            = "; STGEN

5870   PRINT "           TURBINE ADIABATIC EFFICIENCY (%)         = "; AEFF

5880   PRINT "           TURBINE MECHANICAL EFFICIENCY (%)        = "; MEFF

5890   PRINT "           ELECTRICAL GENERATOR EFFICIENCY (%)      = "; GEFF

5900   PRINT
```

```
5650 LPRINT "            EVAPORATOR DUTY (MMBTU/hr)                       = ";
     : LPRINT USING "####.##"; QEVA / 1000000!

5660 LPRINT "            ECONOMIZER DUTY (MMBTU/hr)                       = ";
     : LPRINT USING "####.##"; QECO / 1000000!

5670 LPRINT ""

5680 LPRINT ""

5690 LPRINT "            STEAM FLOW AT MAIN STEAM STOP VALVE (x 1,000 lb/h) = ";
     : LPRINT USING "####.##"; STGEN / 1000

5700 LPRINT

5710 LPRINT "          ---------------------------------------------------------"

5720 GOTO 6720

5730 REM

5740 LOCATE 23, 29: COLOR 17, 15: PRINT "PRESS ANY KEY TO CONTINUE": COLOR 7, 0

5750 P$ = INKEY$: IF P$ = "" THEN 5750

5760 CLS

5770 REM --------------------------------------------------------------------

5780 REM                 INPUT DATA AND OUTPUT RESULTS ECHOED ON SCREEN

5790 REM --------------------------------------------------------------------

5800  PRINT "                            TURBINE - GENERATOR DATA"

5810  PRINT "                            ------------------------"

5820  PRINT

5830  PRINT "          STEAM INLET PRESSURE (PSIA)              = "; ESPMSSV

5840  PRINT "          STEAM INLET TEMPERATURE (½F)             = "; ESTMSSV

5850  PRINT "          STEAM EXIT PRESSURE (PSIA)               = "; EP

5860  PRINT "          STEAM MASS FLOW RATE (lb/sec)            = "; STGEN

5870  PRINT "          TURBINE ADIABATIC EFFICIENCY (%)         = "; AEFF

5880  PRINT "          TURBINE MECHANICAL EFFICIENCY (%)        = "; MEFF

5890  PRINT "          ELECTRICAL GENERATOR EFFICIENCY (%)      = "; GEFF

5900  PRINT
```

```
5910   PRINT "                    POWER GENERATION POTENTIAL IN SG MODULE"
5920   PRINT "                    ---------------------------------------"
5930   PRINT
5940   PRINT "         ENTHALPY OF INLET STEAM (BTU/lb)            = "; HEAT1
5950   PRINT "         ENTROPY OF INLET STEAM (BTU/lb/½F)          = "; ENTR1
5960   PRINT "         ENTHALPY AT EXIT-Ideal Cond (BTU/lb)        = "; IHEAT2
5970   PRINT "         ENTHALPY AT EXIT-Actual Cond (BTU/lb)       = "; AHEA2
5980   PRINT "         ENTROPY AT EXIT-Actual Cond (BTU/lb/½F)     = "; OUTENT
5990   PRINT "         MOISTURE IN EXHAUST STEAM (%)               = "; QUAL*100
6000   PRINT "         ELECTRICAL POWER (MWe)                      = "; POWER/1000
6010   PRINT
6020   LOCATE 22, 11: PRINT STRING$(55, 205)
6030   REM --------------------------------------------------------------
6040   REM             ROUTINE TO PRINT INPUT DATA AND RESULTS
6050   REM --------------------------------------------------------------
6060   PRINT "         WANT A HARD COPY OF THE RESULTS (Y/N) ": YN$ = INPUT$(1)
6070   IF YN$ = "Y" OR YN$ = "y" GOTO 6100
6080   IF YN$ = "N" OR YN$ = "n" GOTO 6720
6090   BEEP: GOTO 6060
6100 LPRINT ""
6110 LPRINT ""
6120 LPRINT ""
6130 LPRINT ""
6140 LPRINT "                         HGPRO  VERSION - 1.0"
6150 LPRINT "       DR. WAYNE C. TURNER, JORGE B. WONG, AND VISWANATHAN GANESH"
6160 LPRINT "               SCHOOL OF INDUSTRIAL ENGINEERING & MANAGEMENT"
6170 LPRINT "             OKLAHOMA STATE UNIVERSITY  STILLWATER  OK 74078"
```

```
6180 LPRINT " "

6190 LPRINT "                    HEAT RECOVERY STEAM GENERATOR (HRSG) ANALYSIS"

6200 LPRINT "                        STEAM FOR ADDITIONAL POWER GENERATION"

6210 LPRINT ""

6220 LPRINT "                        GAS TURBINE MODEL NUMBER: "; MODNO$

6230 LPRINT " "

6240 LPRINT "                                                         "; DATE$

6250 LPRINT "                                                         "; TIME$

6260 LPRINT ""

6270 LPRINT "        ----------------------------------------------------"

6280 LPRINT ""

6290 LPRINT "         GAS TURBINE "

6300 LPRINT "         ----------- "

6310 LPRINT " "

6320 LPRINT "         GAS TURBINE EXHAUST FLOW RATE (lb/s)           = ";
      : LPRINT USING "####.##"; EGTF

6330 LPRINT "         GAS TURBINE EXHAUST TEMPERATURE (½F)           = ";
      : LPRINT USING "####.##"; EGT1

6340 LPRINT ""

6350 LPRINT "         HEAT RECOVERY STEAM GENERATOR "

6360 LPRINT "         ----------------------------- "

6370 LPRINT " "

6380 LPRINT "      TEMP. OF EXHAUST GAS ENTERING SUPER HEATER (½F)    = ";
      : LPRINT USING "####.##"; EGT1

6390 LPRINT "      TEMP. OF EXHAUST GAS ENTERING EVAPORATOR (½F)      = ";
      : LPRINT USING "####.##"; EGT2

6400 LPRINT "      TEMP. OF EXHAUST GAS ENTERING ECONOMIZER (½F)      = ";
      : LPRINT USING "####.##"; EGT3

6410 LPRINT "      TEMPERATURE OF WATER ENTERING ECONOMIZER (½F)      = ";
      : LPRINT USING "####.##"; ETF1
```

```
6420 LPRINT "             SATURATION TEMPERATURE (½F)                        = ";
     : LPRINT USING "####.##"; ETSAT

6430 LPRINT "             PRESSURE LOSS IN VALVES, LINKS, & SH COIL (psig)    = ";
     : LPRINT USING "####.##"; ELOSS

6440 LPRINT "             HRSG DRUM OPERATING PRESSURE (psig)                = ";
     : LPRINT USING "####.##"; EDOP

6450 LPRINT "             BOILER BLOW DOWN (x 1000 lbm/hr)                   = ";
     : LPRINT USING "####.##"; BLOWDOWN / 1000

6460 LPRINT "             TEMPERATURE OF STEAM AT MAIN STEAM STOP VALVE (½F) = ";
     : LPRINT USING "####.##"; ESTMSSV

6470 LPRINT "             PRESSURE OF STEAM AT MAIN STEAM STOP VALVE (psig)  = ";
     : LPRINT USING "####.##"; ESPMSSV

6480 LPRINT "             PINCH POINT (½F)                                   = ";
     : LPRINT USING "####.##"; EPP

6490 LPRINT "             APPROACH POINT (½F)                                = ";
     : LPRINT USING "####.##"; EAPP

6500 LPRINT "             SUPERHEATER DUTY (MMBTU/hr)                        = ";
     : LPRINT USING "####.##"; QSH / 1000000!

6510 LPRINT "             EVAPORATOR DUTY (MMBTU/hr)                         = ";
     : LPRINT USING "####.##"; QEVA / 1000000!

6520 LPRINT "             ECONOMIZER DUTY (MMBTU/hr)                         = ";
     : LPRINT USING "####.##"; QECO / 1000000!

6530 LPRINT "             STEAM FLOW AT MAIN STEAM STOP VALVE (x 1,000 lb/h) = ";
     : LPRINT USING "####.##"; STGEN / 1000

6540 LPRINT

6550 LPRINT "             STEAM TURBINE GENERATOR"

6560 LPRINT "             ----------------------- "

6570 LPRINT "             STEAM EXIT PRESSURE (psia)                         = ";
     : LPRINT USING "####.##"; EP

6580 LPRINT "             TURBINE ADIABATIC EFFICIENCY (%)                   = ";
     : LPRINT USING "####.##"; AEFF

6590 LPRINT "             TURBINE MECHANICAL EFFICIENCY (%)                  = ";
     : LPRINT USING "####.##"; MEFF

6600 LPRINT "             ELECTRICAL GENERATOR EFFICIENCY (%)                = ";
     : LPRINT USING "####.##"; GEFF
```

```
6610 LPRINT

6620 LPRINT "                ENTHALPY OF INLET STEAM (BTU/lbm)                    = ";
     : LPRINT USING "####.##"; HEAT1

6630 LPRINT "                ENTROPY OF INLET STEAM (BTU/lbm-½F)                  = ";
     : LPRINT USING "####.##"; ENTR1

6640 LPRINT "                ENTHALPY AT EXIT-Ideal Conditions (BTU/lbm)          = ";
     : LPRINT USING "####.##"; IHEAT2

6650 LPRINT "                ENTHALPY AT EXIT-Actual Conditions (BTU/lbm)         = ";
     : LPRINT USING "####.##"; AHEA2

6660 LPRINT "                ENTROPY AT EXIT-Actual Conditions (BTU/lbm-½F)       = ";
     : LPRINT USING "####.##"; OUTENT

6670 LPRINT "                MOISTURE IN EXHAUST STEAM (%)                        = ";
     : LPRINT USING "####.##"; QUAL * 100

6680 LPRINT "                ELECTRICAL POWER (MWe)                               = ";
     : LPRINT USING "####.##"; POWER / 1000

6690 LPRINT

6700 LPRINT "               -----------------------------------------------------"

6710 REM

6720 CLS

6730 LOCATE 8, 6: PRINT STRING$(72, 220)

6740 LOCATE 17, 6: PRINT STRING$(72, 220)

6750 LOCATE 13, 18: COLOR 17, 15: PRINT "RUN AGAIN FOR DIFFERENT INPUT DATA
     (Y/N):  ": COLOR 7, 0

6760 A$ = INPUT$(1): LOCATE 13, 60: PRINT A$

6770 IF A$ = "y" OR A$ = "Y" THEN 460

6780 IF A$ = "n" OR A$ = "N" THEN 6820

6790 BEEP: LOCATE 23, 60: PRINT " ": GOTO 6750

6800 CLS : SYSTEM
```

CHAPTER 4 - RESULTS AND DISCUSSION

4.0 RESULTS AND DISCUSSION

The routine "HGPRO" was developed to run under Disk Operating System using QuickBasic as the platform.

The highlight of the program is that it uses ASME formulations for computing steam/compressed water properties and curve fit equations for specific heat of exhaust gases. The program has several in-built "error trapping" routines which validates the user input at different points and produces results only for practical and meaningful input data. Also, the user is prompted about possible causes for the error and returned to the appropriate point within the program to re-enter the required data.

The program was verified by splitting the program into different modules and verifying the output from the module for a given set of inputs.

The program was validated using the actual performance parameters as the bench mark given in reference [20]. The results agreed very well and the differences between the values computed by "HGPRO" and those given in reference [20] were less than 1%.

I sincerely hope that the energy professionals involved in cogeneration and independent power production feasibility studies find the software handy and useful.

5.0 SCOPE FOR FURTHER RESEARCH

The HGPRO analyses GT/HRSG only in the unfired mode. By incorporating data on heating values of natural gas, duct burners, etc., the routine can be easily extended to supplementary fired and furnace fired systems.

Typical operating parameters for the commercially available turbines can be put in a database and can form input to "HGPRO".

The optimum size of HRSG behind a gas turbine is dependent on a number of parameters like pinch point, approach point, altitude of the gas turbine installation, ambient conditions, cost of natural gas, cost of heat exchanger, operating hours, turbine part load factor, rate of return from the project, etc.

The pinch and approach points are a function of the heat transfer surface areas in different boiler sections. The optimal surface areas are functions of pressure drop, natural gas cost, and heat exchanger cost. Hence, arriving at the overall optimum techno-economic optimum design requires an iterative technique.

The Economic analysis module to compare different HRSG designs and arriving at the optimum design for an application is a project by itself, and once developed, can be easily incorporated in the "HGPRO" routine.

APPENDIX 1

FLOW CHART FOR "HGPRO" ROUTINE

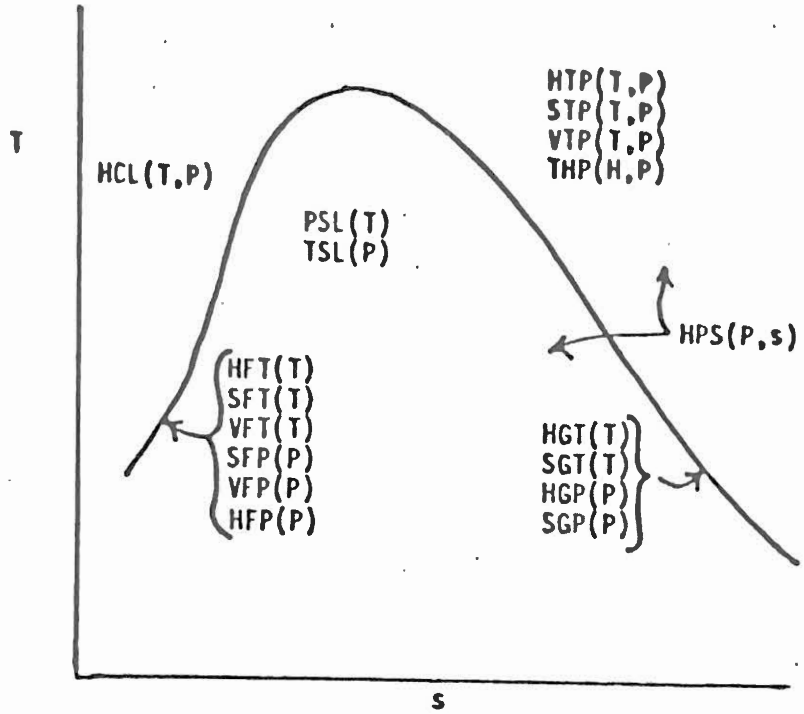
APPENDIX 1 - FLOWCHART FOR "HGPRO" ROUTINE

NOTATIONS USED IN THE MAIN ROUTINE:

Gas Turbine Model Number:	MODNO
Gas Turbine Exhaust Flow Rate (lbm/s):	EGTF
Gas Turbine Exhaust Temperature (°F):	EGT1
Steam Exit Pressure from Turbine (psia):	EP
Turbine Adiabatic Efficiency (%):	AEFF
Turbine Mechanical Efficiency (%):	MEFF
Electrical Generator Efficiency (%):	GEFF
Steam Pressure at MSSV (psia):	ESPMSSV
Steam Temperature at MSSV (°F):	ESTMSSV
Feed Water Temperature (°F):	ETF1
Pinch Point (°F):	EPP
Approach Point (°F):	EAPP
Line Losses (psia):	ELOSS
Steam Temperature at MSSV (°F) (as calculated by the routine):	TSL
Drum Operating Pressure (psia):	EDOP
Saturation Temperature (°F):	ETSAT
Gas Temperature at Superheater Inlet (°F):	EGT1
Gas Temperature at Evaporator Inlet (°F):	EGT2
Gas Temperature at Economizer Inlet (°F):	EGT3
Gas Temperature at HRSG Outlet (°F):	EGT4
Enthalpy of Gas at Superheater Inlet (Btu/lbm):	HG1
Enthalpy of Gas at Evaporator Inlet (Btu/lbm):	HG2
Enthalpy of Gas at Economizer Inlet (Btu/lbm):	HG3
Enthalpy of Gas at HRSG Outlet (Btu/lbm):	HG4
Steam Generated (lbm/s):	STGEN
Enthalpy at Turbine Inlet (Btu/lbm):	HEAT1
Enthalpy at Turbine Outlet (Btu/lbm):	IHEAT2
Enthalpy Drop across Turbine (Btu/lbm):	AHEA2
Steam Quality (%):	QUAL
Power Generated in Steam Turbine (MW_e):	POWER

NOTATIONS USED IN THE SUBROUTINE STEAM:

The notations used in the subroutine to compute steam properties is best illustrated by the figure [19] given in next page.



UNITS USED

T = °F

P = PSIA

h = Btu/lbm

s = Btu/lbm°R

v = ft^3/lbm

SUPERHEATED VAPOR

HTP(T,P) = h(T,P)

STP(T,P) = s(T,P)

VTP(T,P) = v(T,P)

THP(H,P) = T(h,P)

SUPERHEATED VAPOR AND SATURATION REGION

HPS(P,s) = h(P,s)

COMPRESSED LIQUID

HCL = h(T,P)

SATURATION LINE

PSL(T) = P(T)

TSL(P) = T(P)

SATURATED VAPOR

HGT(T) = h_g(T)

HGP(P) = h_g(P)

SGT(T) = s_g(T)

SGP(P) = s_g(P)

SATURATED LIQUID

HFT(T) = h_f(T)

HFP(P) = h_f(P)

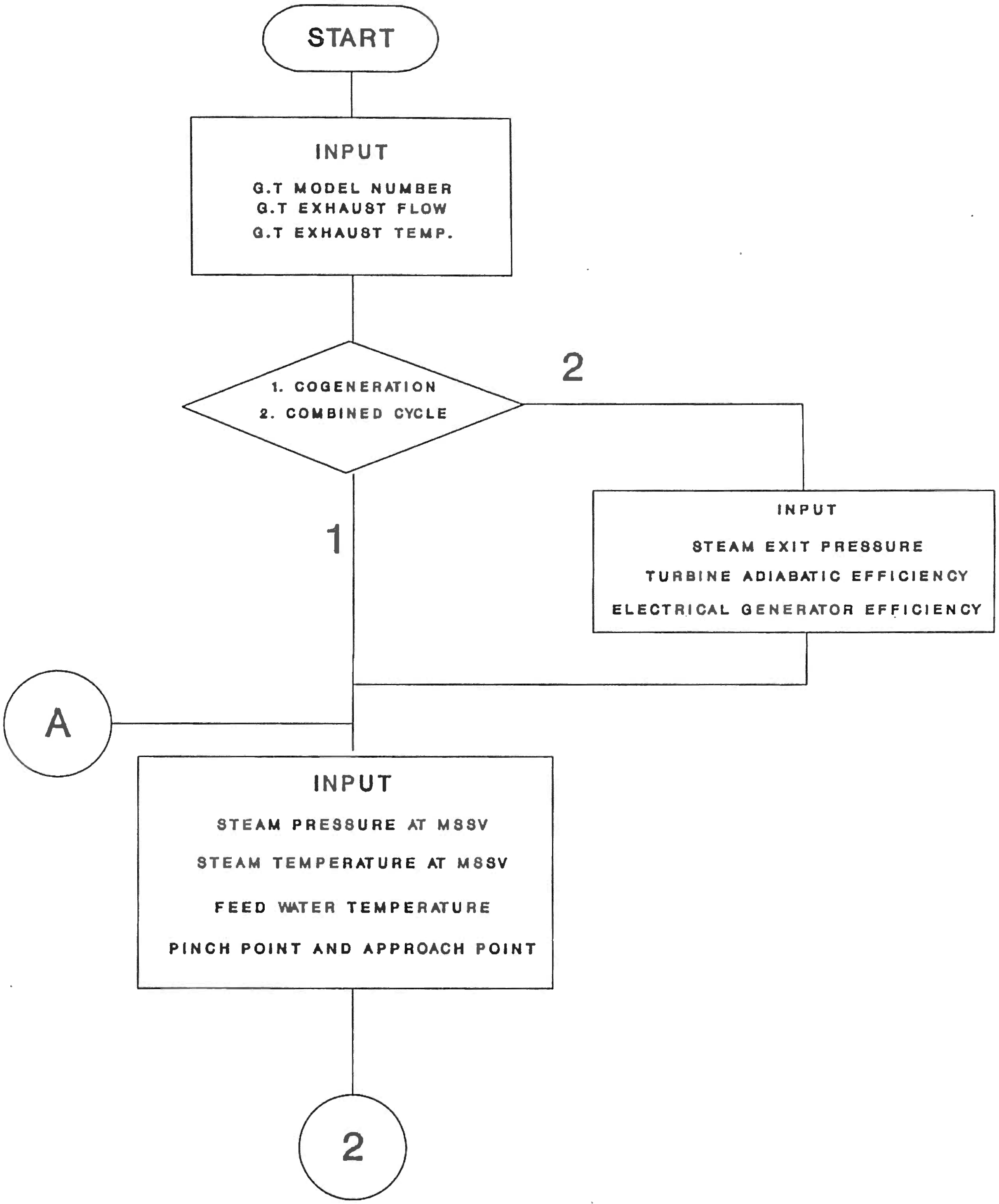
SFT(T) = s_f(T)

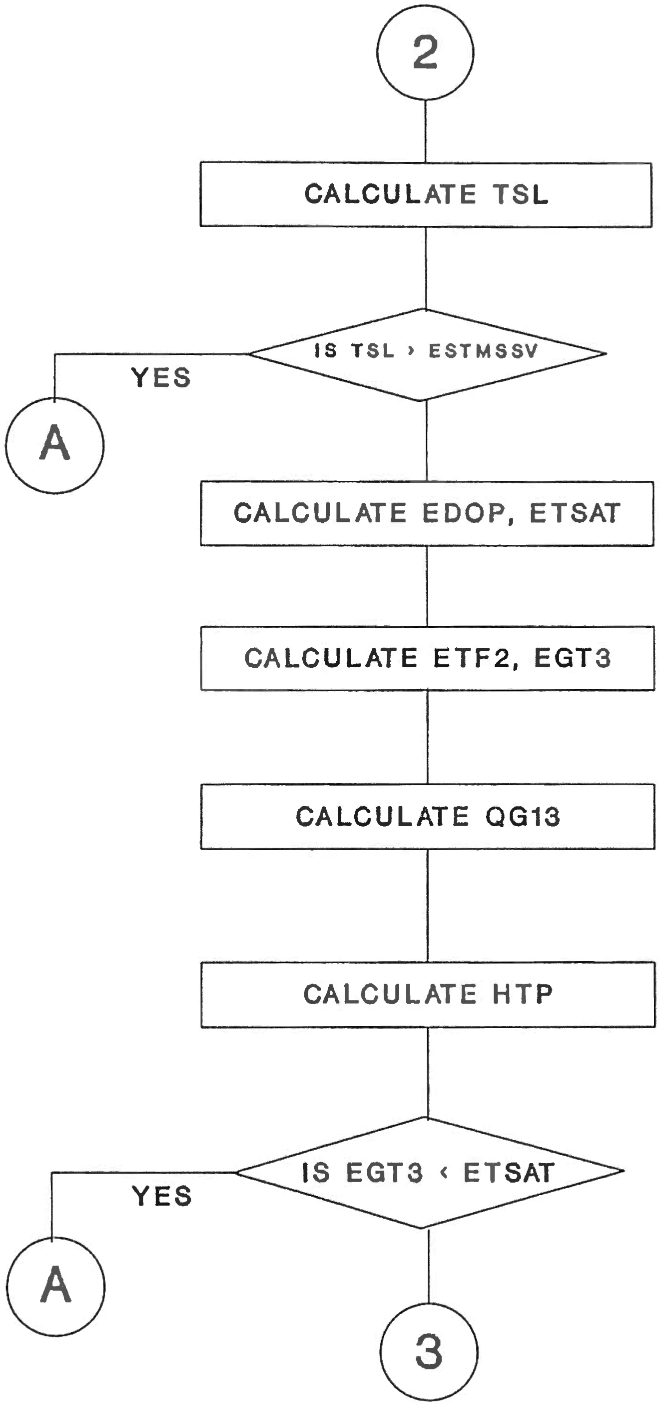
SFP(P) = s_f(P)

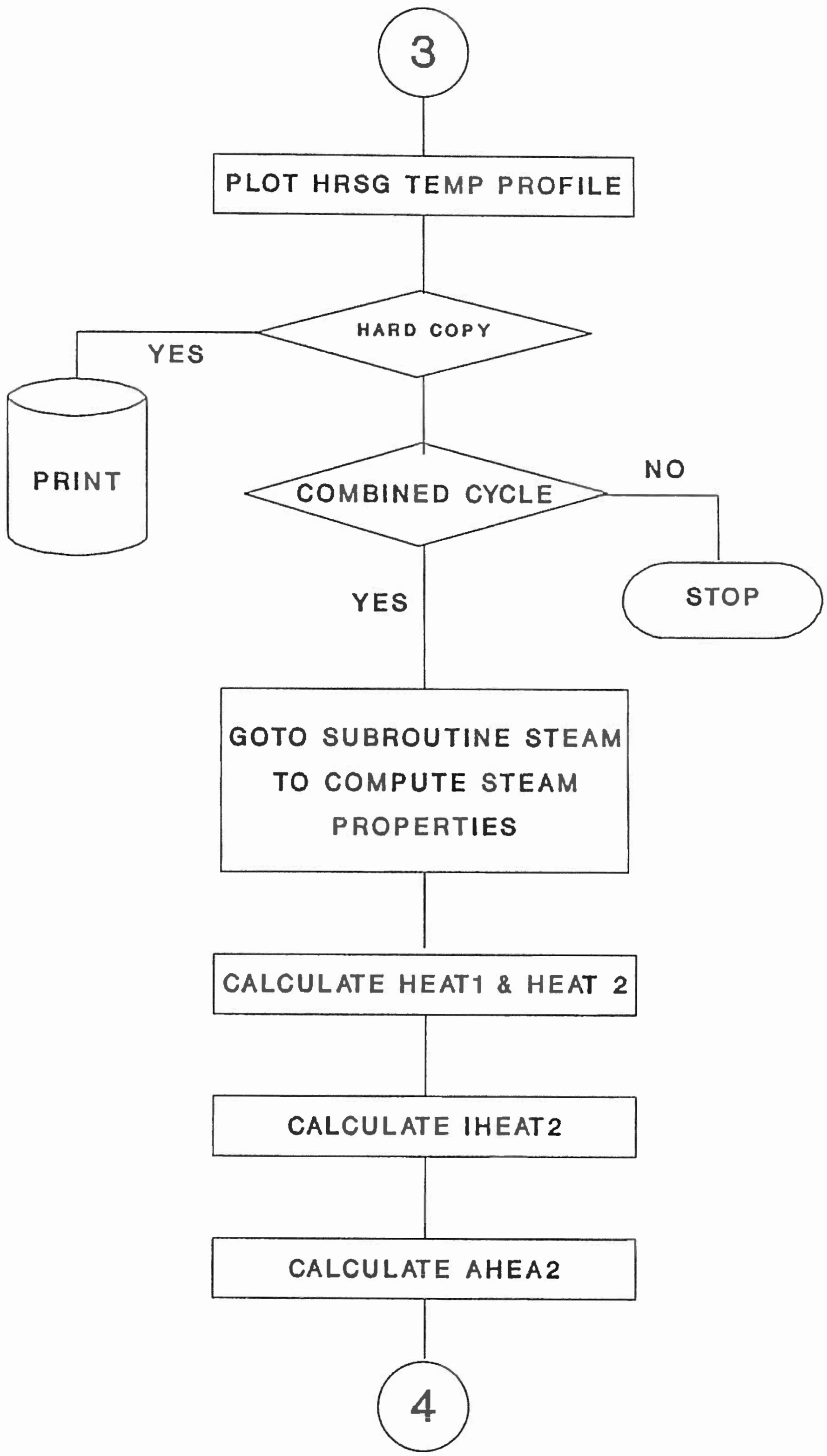
VFP(P) = v_f(P)

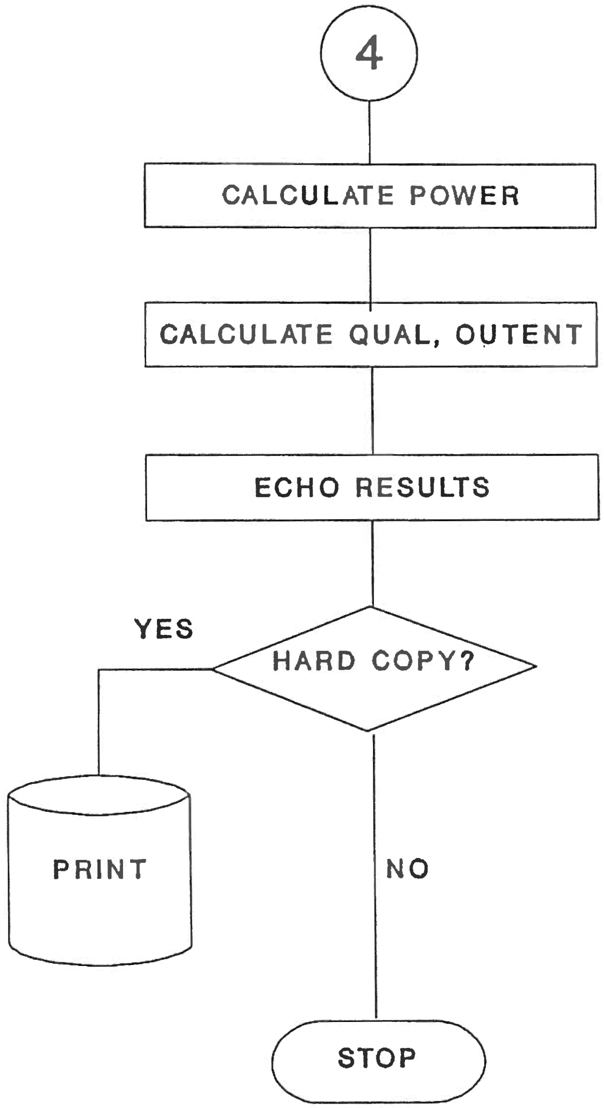
VFT(T) = v_f(T)

FUNCTIONS TO COMPUTE STEAM PROPERTIES [19]


START
INPUT
G.T MODEL NUMBER
G.T EXHAUST FLOW
G.T EXHAUST TEMP.
1. COGENERATION
2. COMBINED CYCLE
2
1
INPUT
STEAM EXIT PRESSURE
TURBINE ADIABATIC EFFICIENCY
ELECTRICAL GENERATOR EFFICIENCY
A
INPUT
STEAM PRESSURE AT MSSV
STEAM TEMPERATURE AT MSSV
FEED WATER TEMPERATURE
PINCH POINT AND APPROACH POINT
2


2
CALCULATE TSL
IS TSL › ESTMSSV
YES
A
CALCULATE EDOP, ETSAT
CALCULATE ETF2, EGT3
CALCULATE QG13
CALCULATE HTP
IS EGT3 ‹ ETSAT
YES
A
3


3
PLOT HRSG TEMP PROFILE
HARD COPY
YES
PRINT
COMBINED CYCLE
NO
STOP
YES
GOTO SUBROUTINE STEAM TO COMPUTE STEAM PROPERTIES
CALCULATE HEAT1 & HEAT 2
CALCULATE IHEAT2
CALCULATE AHEA2
4


4
CALCULATE POWER
CALCULATE QUAL, OUTENT
ECHO RESULTS
YES
HARD COPY?
PRINT
NO
STOP

APPENDIX 2

"HGPRO" USER'S GUIDE

APPENDIX 2 - "HGPRO" USERS GUIDE

1] Insert the diskette in drive A and type install at A:\> prompt. This will create a directory named HGPRO in C drive and copy the HGPRO routine to the hard drive. If you choose not to install the routine in C drive go to step 3.

2] At c:\HGPRO> type HGPRO to invoke the routine.

3] To execute HGPRO from A:\> type HGPRO at A:\> prompt.

4] HGPRO will show the initial information screen and will prompt the user to press and key to continue.

5] At the input module screen enter the following information:

Gas Turbine Module Number

Gas Turbine Exhaust Flow Rate (lbm/sec)

Gas Turbine Exhaust Temperature (°F)

All the above information can be obtained from the manufacturer's catalog.

6] HGPRO will prompt the user to choose one of the following options:

Choose option 1 for calculating steam generation potential for industrial process (cogeneration)

Choose option 2 for calculating steam generation + power generation potential (combined cycle)

If option 1 is chosen HGPRO will automatically skip step 7

7] If option 2 is chosen, the routine will prompt to enter the following details pertaining to steam turbine generation:

Steam Exit Pressure (Psia)

Turbine Adiabatic Efficiency (%)

Turbine Mechanical Efficiency (%)

Electrical Generator Efficiency (%)

The user is cautioned to input the required information in proper units (units will be echoed on the screen)

8] HGPRO will then prompt the user to input the following details pertaining to the Heat Recovery Steam Generator.

Steam Pressure at MSSV (lb/in^2)

Steam Temperature at MSSV (°F)

Pinch Point (°F)

Approach Point (°F)

Valves + Lines + Links Losses (lb/in^2)

If cogeneration option is chosen, the steam pressure and temperature is dependent on the process requirements. If combined cycle option is chosen, maximum steam pressure and temperature (limitation being the exit temperature of the exhaust gas - terminal temperature difference) must be chosen to take advantage of the Rankine cycle.

Pinch Point and Approach Point are dependent on the natural gas cost and area of the heat exchanger surface. For preliminary analysis of the project a pinch point of 30 °F and approach point of 30 °F would be appropriate.

9] HGPRO will calculate the saturation steam temperature and if the steam temperature at Main Steam Stop Valve is less than the saturation temperature, HGPRO will flag an error and will return the user to the input module.

10] After the above validation "HGPRO" will run all the calculations and the following will be calculated:

1. Gas enthalpy drop across superheater, evaporator, and economizer.
2. Water/Steam enthalpy rise across economizer, evaporator, and superheater.
3. Duties of superheater, evaporator, and economizer.

If the Pinch Point and Approach Point selected by the user is very less and should any conflict occur in the energy and mass balance at any stage, an error will be flagged by "HGPRO" and the user will be returned to the input module.

11] The routine will then echo the results pertaining to Heat Recovery Steam Generator design on the screen along with the temperature profile. If the user desires to print a hard copy of the graphics, the DOS program "GRAPHICS.COM" must be executed before starting the routine. Hard copy of the results in text format can be obtained by selecting the appropriate option at the end of the routine.

12] If combined cycle option (option 2) was chosen by the user, the additional power output potential will also be echoed on the screen. A detailed hard copy of the results can be obtained by selecting the appropriate option.

13] At the end of the routine, the user has the option to run the routine for a different set of input or to terminate the program.

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