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Coal-Fired High Performance Power Generating System

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Prepared for

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EXECUTIVE SUMMARY

This report covers work carried out under Task 3, Preliminary R and D, under contract DE-AC22-92PC91155, "Engineering Development of a Coal-Fired High Performance Power Generation System" between DOE Pittsburgh Energy Technology Center and United Technologies Research Center.

The goals of the program are to develop a coal-fired high performance power generation system (HIPPS) by the year 2000 that is capable of

- $>47\%$ thermal efficiency
- NO_x, SO_x and particulates $\leq 25\%$ NSPS
- cost $\geq 65\%$ of heat input
- all solid wastes benign

A crucial aspect of our design is the integration of the gas turbine requirements with the HITAF output and steam cycle requirements. In order to take full advantage of modern highly efficient aeroderivative gas turbines we have carried out a large number of cycle calculations to optimize our commercial plant designs for both greenfield and repowering applications.

AERO-DERIVATIVE GAS TURBINE/HITAF SYSTEMS

Introduction

A commercial plant design has been described in a previous quarterly report. This design was based on the use of a heavy frame-type gas turbine similar to the Siemens V84.3A. In addition to heavy frame machines, UTRC was requested by DoE/METC to investigate the use of aeroderivative gas turbines in conjunction with the High Temperature Advanced Furnace (HITAF).

Definition of Aero-derivative

An aero-derivative gas turbine is one that is based on components originally developed for aircraft application. These components are generally lighter in weight and higher in performance than heavy frame machines. Over the years, aero-derivative gas turbines such as UTC's FT3, FT4, and FT8 and GE's LM2500 and LM6000 have been successfully applied to peaking (<500 hr/yr) and intermediate duty (1000-5000 hr/yr) in both simple and combined-cycle configurations. They have also been used as industrial cogenerators running as baseload (>6500 hr/yr) machines. These engines have displayed reliabilities equivalent to heavy frame machines and, usually, greater availability because of the shorter down times required to replace critical components.

Their applications, however, have been limited to some degree by their small outputs, e.g., 25-35 MW per unit. Many applications gang the engines so that multiple engines exhaust into a single HRSG for combined-cycle plants of 100-200 MW. The advent of the very high thrust (>60,000 lb) aircraft turbines gave promise to larger aero-derivative gas turbines of 40-50 MW. For example, Pratt & Whitney has developed a 60-98,000 lb. thrust engine, the PW4000, Fig. 1. This engine has been in commercial service for several years on such aircraft as the Boeing 747, 767, and the new 777 as well as the MD-11 and Airbus. Industrial versions of this engine have been proposed such as that shown in Fig. 2.

Technology Advantages

The engine shown in Fig. 2 has multiple spools, i.e., it has separate high pressure and low pressure sections that operate at speeds close to their optimum. The multiple spool approach has several technology advantages.

Large electric generators turn at 3600 rpm (3000 rpm in 50 cycle applications). This means that the power shaft of the gas turbine must turn at 3600 rpm, unless a costly gear box is used. A single shaft machine then is limited to 3000/3600 rpm, meaning that it must be large enough to pass the air flows necessary for high power, greater than 100 MW, output. Large parts such as turbine blades are more difficult to cool than the smaller blades used in the higher pressure ratio aero-derivatives. This results in higher cooling penalties.

Pressure ratios for single shaft machines are generally limited to less than 20 because compressor length gets bigger leading to requiring longer shafts and eventually leading to bearing limitations.

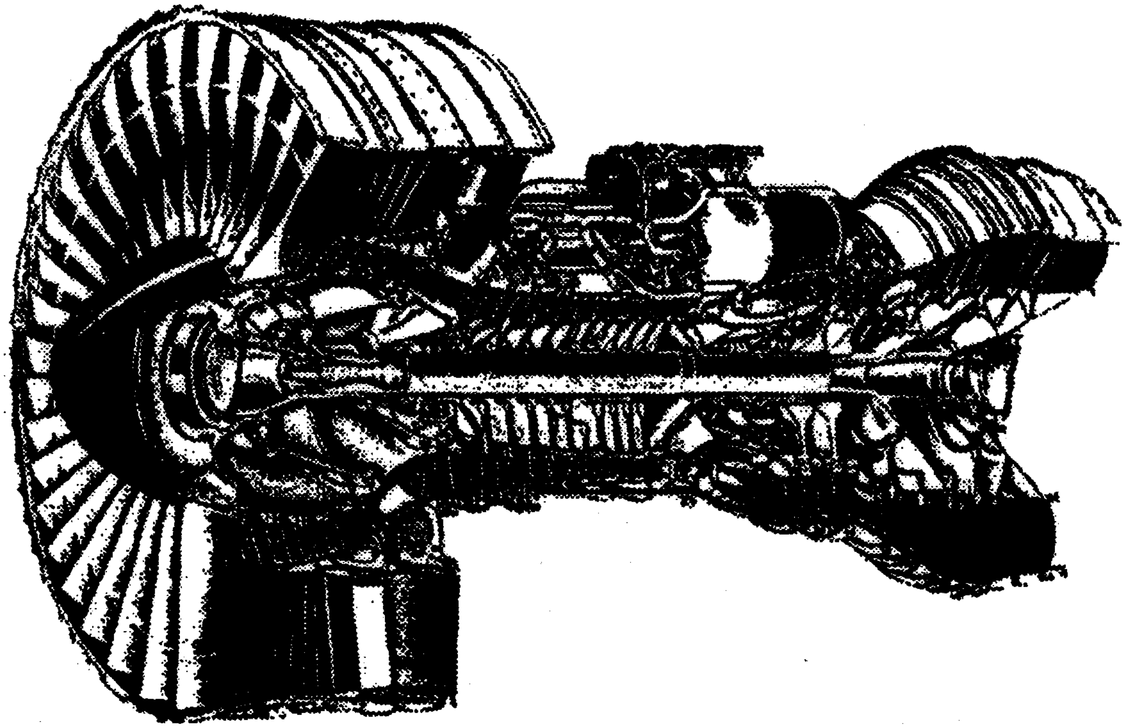

Figure 1. Cutaway of PW4000.

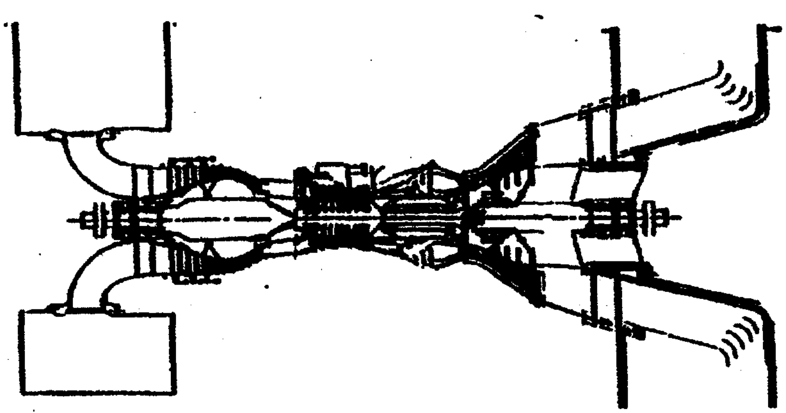

Figure 2. FT4000 Cross Section.

Also, start up and part load operation of high pressure ratio single shaft machines requires many stages of movable inlet guide vanes (IGV) and of air bypass.

The application of aircraft turbine technology to large-scale utility use can be accomplished in two ways: 1) the introduction of the advanced aerodynamics and turbine cooling techniques to large, heavy frame machines; and 2) the development of advanced power cycles taking direct advantage of the high pressure ratios and high turbine temperatures. The first method is being practiced by most aircraft turbine manufactures. At the present time, UTC is supplying state-of-the-art technology to Siemens for use in their V-series of heavy frame machines. This technology transfer can be relatively slow and may not take full advantage of the advanced technology.

Under normal development conditions, the manufacturers of gas turbines will make only small, incremental advances in turbine technology over the next several years. While these turbines can be used in power systems having efficiencies around 55% (LHV), further advances can be made only by significant cycle and turbine modification. This is because machines appearing in the mid-1990 decade will have essentially reached the plateau of current turbine cooling technology based on extraction air. The attainment of higher efficiencies combined with lower emissions and comparable cost of electricity will require cycle and machinery changes including, among others, intercooling, improved turbine cooling, flow augmentation by steam or water vapor, and combustor and turbine material improvements. These advances are more readily realized in the smaller component sizes and multiple spool arrangements typical of aero-derivative engines.

Another technology advantage of the aero-derivative machines relates to their physical size. The heavy frame-type machines also have a larger footprint which is an important consideration in may utility plant sites.

Baseline Commercial Power Plant

A preliminary aero-derivative gas turbine baseline power plant configuration has been identified. This plant is based on the FT4000 IC, an intercooled version of the FT4000 shown in Fig. 2.

FT4000 IC

The simple-cycle FT4000, shown in Fig. 2, has been modified to an intercooled configuration (Fig. 3) to obtain more power. The high-pressure (HP) spool, which represents the largest development cost of an engine, remains the same. Intercooling allows more power output in two way: first, intercooling reduces compressor work (a cooler gas requires less work to compress it); and, secondly, for a fixed HP spool, the low pressure (LP) spool can pass more air. (The "swallowing" capacity of the HP spool is constant, thus, more lower temperature air can be passed through.)

Engine Performance

The estimated performance of the natural gas-fired version FT4000 IC shown in Fig. 3 is given in Table 1.

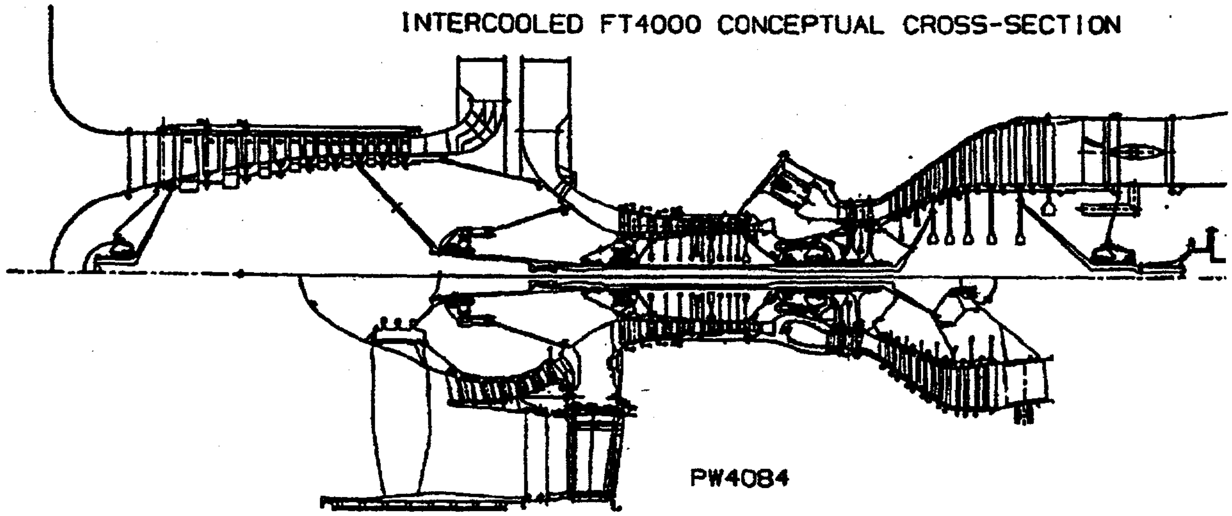

Figure 3. FT4000 IC.

Table 1. FT4000 IC Estimated Performance (4 in./4 in.Losses, 98% Generator Efficiency)

Generator Output, MW	114
Efficiency, %	44.9
Combustor Exit Temp., °F	2700
Inlet Flow Rate, lb./sec	509
Pressure Ratio	48.4
Exhaust Temp., °F	749

System Definition

The FT4000 IC HIPPS conceptual design (see Fig. 4 for a simplified schematic), developed by the Combustion 2000 Team, is based on advanced gas turbine technology, which could be commercialized by the year 2000. The three major elements of the system are the High Temperature Air Furnace (HITAF), the gas turbine, and the steam turbine. The HITAF supplies air heated to about 1700°F to a duct burner where natural gas boosts the temperature to that required by the turbine. The turbine exhaust stream, along with that from the HITAF, furnishes waste heat to a heat recovery steam generator (HRSG) and steam turbine. The overall efficiency of this system exceeds 48%, approximately 35% better than typical PC plants.

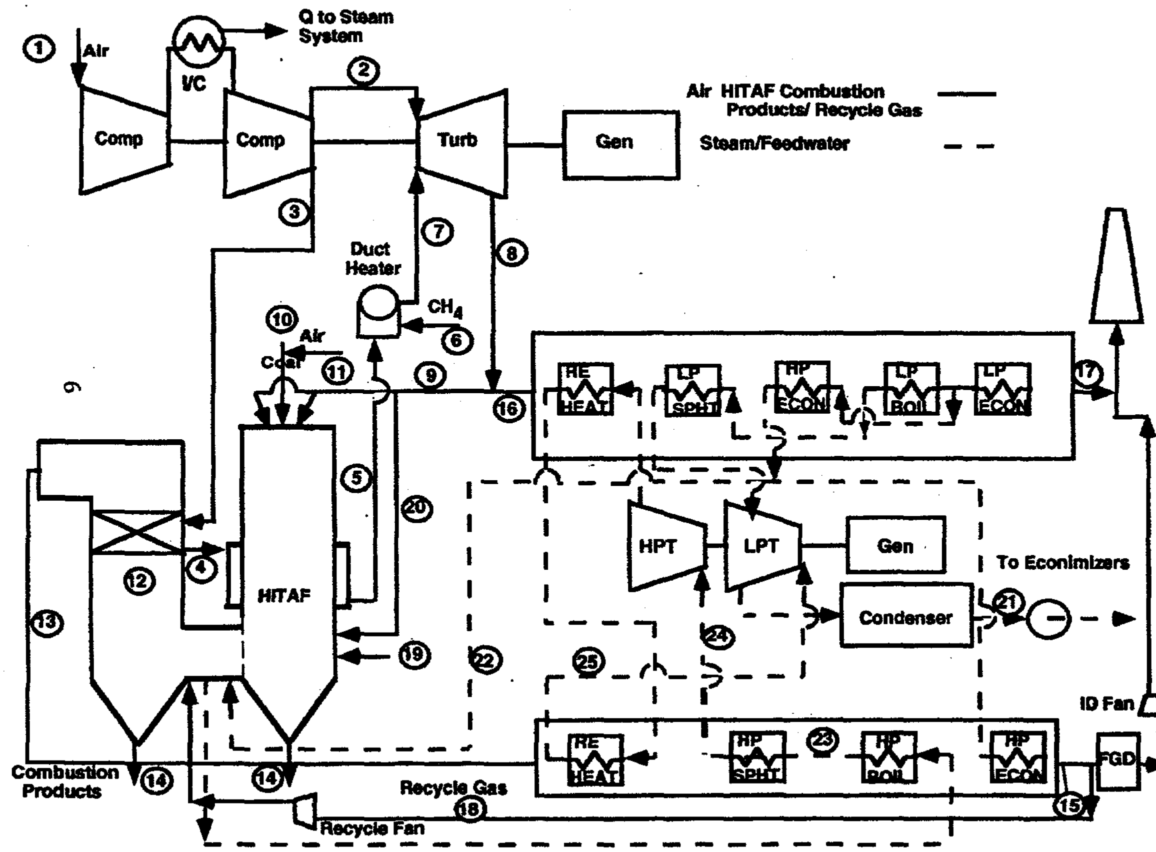

Figure 4. Combined Cycle HITAF with FT4000.

In Fig. 4, it can be seen that the compressor discharge air is sent to a convective air heater in the HITAF. From there, it goes to a radiant heater located in the highest temperature portion of the HITAF, and then to the duct heater where the temperature is raised to the required combustor exit level. The exhaust from the gas turbine is split; one portion is sent to a "clean" HRSG, while the remainder is used as preheated combustion air for the coal (Illinois No. 6) in the HITAF. The exhaust from the HITAF is sent to a "dirty" HRSG, baghouse, and FGD. To maintain the temperature required for a selective non-catalytic converter in the HITAF, as well as assure that the temperature for the convective section does not exceed 1800°F, a portion of the HITAF exhaust is recirculated. The steam bottoming system is atypical of currently installed combined cycles, with higher operating conditions of 2400 psi/1050°F/1050°F.

System Performance

A heat and mass balance for the Fig. 4 configuration is given in Table 2. Here it is seen that the net power plant output is approximately 212 MW and the estimated overall efficiency is 48.5%.

Table 2. Heat and Mass Balance for Baseline FT4000 Combined Cycle

Point No.	Fluid	Temp - F	Pressure - PSIA	Flow - lb/sec	Comments
1	Air	57	14.7	509.2	
2	Air	710	701	106.2	
3	Air	710	701	403	
4	Air	1300	691	403	
5	Air	1700	680	403	
6	Methane	70	750	6.1	After Heater
7	Air	2700	657	409.1	
8	GT Exhaust	751	15.5	515.2	
9	GT Exhaust	751	15.5	264.5	
10	Coal	138	22	21.4	
11	Air	138	22	37.1	
12	HITAF Ex.	1800	14.2	465.6	
13	Flue Gas	1360	13.9	465.6	
14	Solid Waste			2.1	Sum of Both Streams
15	HITAF Ex.	240	13	465.6	
16	GT Exhaust	751	15.5	250.7	
17	GT Exhaust	180	14	574.3	T0 Induced Draft Fan
18	RecycleGas	258	14.7	145.1	Recycle for Quench
19	Coal Fines				Reburn - Inc in 10 (8%)
20	GT Exhaust	751	15.5	49.4	Excess Air (20%)
21	Condensate	91	0.75	157.7	
22	Feedwater	682	3100	143	
23	Sat. Steam	682	2750	141.6	From HITAF Waterwall
24	Steam	1050	2400	141.6	
25	Steam	1050	540	141.6	

Gas Turbine Output - MW	120
Steam Turbine Output - MW	101
System Efficiency - per cent	48.5

FT4000 HAT

The advent of the high pressure ratio, FT4000 IC engine allows consideration of an advanced power cycle using a saturator to supply humidified air to the turbine. The Humid Air Turbine (HAT) cycle has been patented by Fluor Daniel, Inc. and has been the subject of a number of joint UTC/Fluor programs in the past several years. These include a TPM/Fluor/Texaco/EPRI study in 1991/92 on integrated coal gasification/HAT and the Cooperative Advanced Gas Turbine study for EPRI and an utility consortium in 1994.

A simplified schematic of a natural-gas fired HAT cycle is shown in Fig. 5. The cycle features a very effective regeneration scheme in which low grade heat from the intercooler, an aftercooler that takes heat from the high compressor discharge, and a turbine exhaust gas exchanger that acts as a regenerator and an economizer. Low-grade heat (<400°F) is used to humidify the compressor discharge resulting in an increase in mass flow through the turbine.

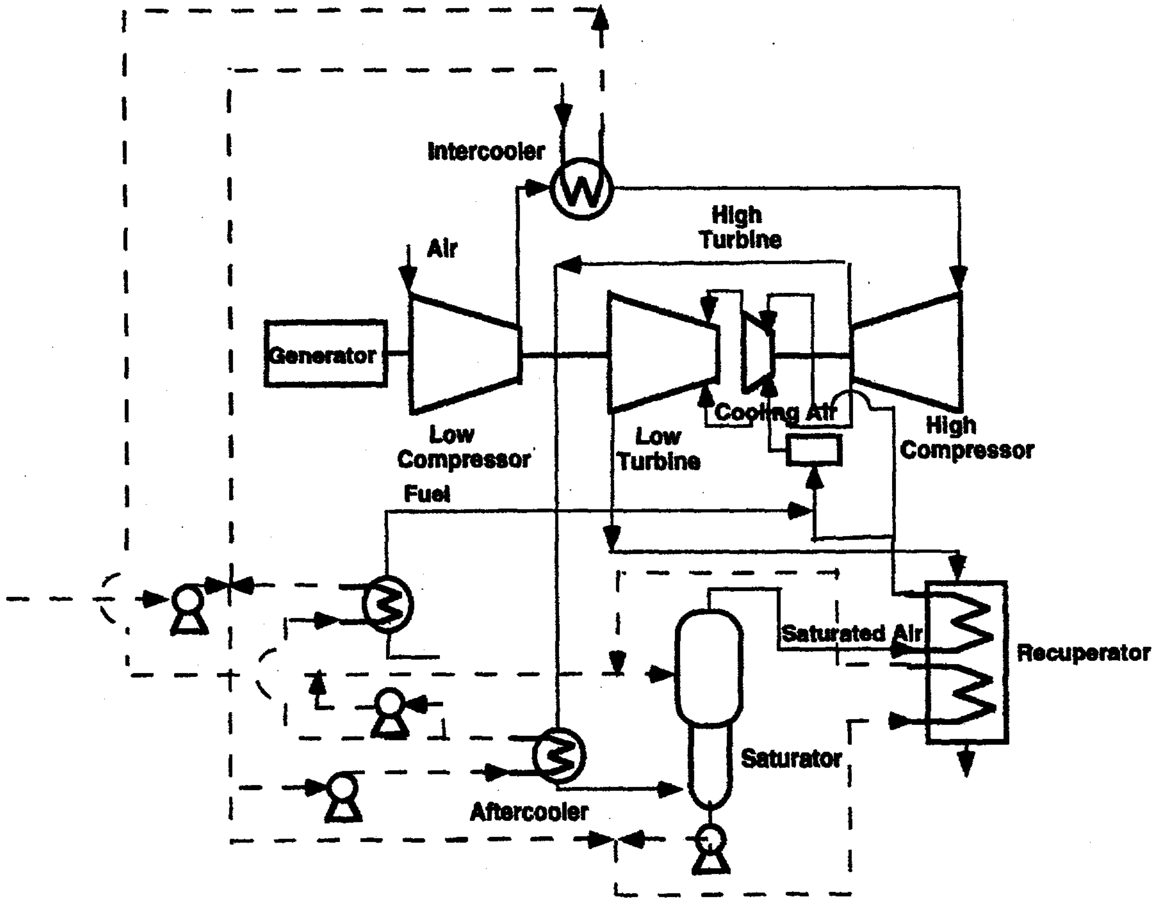

Figure 5. Natural Gas-Fired HAT Cycle.

Engine performance

The estimated performance of the natural gas-fired version FT4000 HAT is given in Table 3.

Table 3. FT4000 HAT Estimated Performance (4 in. inlet loss, 98% Generator Efficiency)

Generator Output, MW	204
Efficiency, %	58.1
Combustor Exit Temp., °F	2700
Inlet Flow Rate, lb./sec	509
Pressure Ratio	48.4
Stack Temp., °F	238

System Definition

The adaptation of the HAT cycle to HIPPS required some changes to the engine described in Table 3. Because of the additional moisture in the gases going to the combustor, more natural gas is required to raise the temperature to the desired combustor exit temperature (2700°F). The DoE ground rule of 65%/35% coal to gas would mean that considerable excess coal would burned; excess in that the high temperature heat from the coal could not be effectively used in the HAT. This excess heat could be recovered as steam for use in a bottoming cycle, but that is counter to the philosophy of the HAT which attains high efficiencies without using steam bottoming. (A HAT /combined-cycle system was also investigated.) Also, to reduce the amount of gas required, the radiator temperature was allowed to reach 1940°F, some 200°F higher than the baseline heavy frame sand baseline FT4000 IC cases. The reasoning being that the HAT cycle system would be appearing in the 2005 time frame, allowing the development of heat exchanger material that would permit the 1940°F temperature.

To make up for the power loss resulting from the lower combustor outlet temperature, the flow through the engine was increased. This was done by removing the last several stages of the high compressor and adding new front stages to the low compressor. A schematic of this system is shown in Fig. 6. Note that the compressor discharge air also passes through the HITAF "waterwall" section. The water-cooled walls were replaced by air-cooling to reduce the amount of steam generated in the cycle.

System Performance

A heat and mass balance for the Fig. 6 configuration is given in Table 4. Here it is seen that the net power plant output is approximately 203 MW and the estimated overall efficiency is 49.5%.

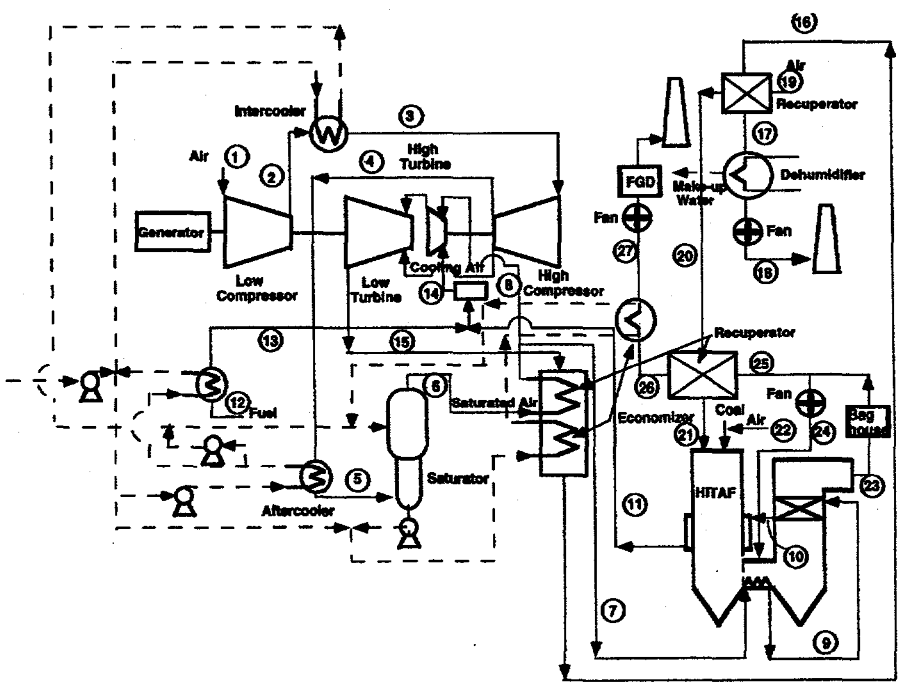

Figure 6. Coal-Fired HITAF Cycle.

Table 4. Heat and Mass Balance for Baseline FT-4000 HAT

Point Number	Fluid	Temp. - F	Pressure -PSIA	Flow - lb/sec	Comment
1	Air	59	14.7	626.9	ISO Conditions
2	Air	492	106.8	626.9	
3	Air	85	98.2	625.4	
4	Air	494	590	507	Less Cooling Air
5	Air	263	573	507	
6	Humid Air	352	562	615.5	Saturator Out
7	Humid Air	767	544	615.5	
8	Humid Air	767	544	55	Vane Cooling
9	Humid Air	913	544	560.6	
10	Humid Air	1390	533	560.6	
11	Humid Air	1975	523	560.6	To Combustor
12	Methane	60	375	5.7	
13	Methane	113	523	5.7	
14	Comb. Prod.	2450	500	566.3	Combustor Exit
15	GT Exhaust	808	15.6	739.6	Turbine Exit
16	GT Exhaust	244	14.9	739.6	
17	GT Exhaust	206	14.9	739.6	
18	GT Exhaust	121	14.9	630.3	After Water Recovery
19	Air	59	14.7	201.8	HITAF Comb. Air
20	Air	220	14.7	201.8	
21	Air	958	14.6	201.8	
22	Air	59	22	24.9	Transport Air
	Coal			19.9	Includes Reburn
23	HITAF Exh'st	1033	9.7	392	
24	HITAF Exh'st	1062	16	148	Recirculation
25	HITAF Exh'st	1033	9.7	244.1	
26	HITAF Exh'st	460	9.6	244.1	
27	HITAF Exh'st	225	9.6	244.1	To Fan/FGD

Gas Turbine Output - MW 202.7
System Efficiency - per cent 49.5

Repowering

Repowering is the upgrading of performance, and usually emissions, of older steam plants through the replacement of obsolescent equipment with newer, higher performance equipment. Repowering generally involves the use of a gas turbine used in a variety configurations to supply heat to new or revised fired-steam boilers/heat recovery steam generators. The U.S. utility industry has a number of older, generally small (<300 MW) steam plants that are candidates for repowering. Between 80 and 90 Gigawatts of power are candidates for repowering, including more than 50 GW of coal-fired systems. Table 5 indicates the potential base for repowering.

Table 5. Potential Repowering Sites

Size – MW	1-99	100-199	200-299
Units	380	430	175
Av. Age – yr..	40	35	30

General Repowering Background

As previously mentioned, there are a variety of repowering options which can be covered by five general categories:

- Substitute HRSG Repowering
- Supplemental HRSG Repowering

- Hot Windbox Repowering
- Feedwater Heating Repowering
- Station Repowering

Each of these will be described briefly since each has features that could be used in a HIPPS approach to repowering. The following summary descriptions are abstracted from EPRI Report:

Substitute HRSG Repowering

A new HRSG replaces the existing boiler and supplies steam to the existing steam turbine generator (Fig. 7). A gas turbine exhausts directly into the HRSG and cooled exhaust gases are discharged to the atmosphere. Major new generation equipment include the gas turbine generator and HRSG. This repowering system has the potential to increase plant output by 160 to 200 percent and plant efficiency by 5 to 30 percent. Environmental emissions are reduced on a per kW basis. Capital costs are typically lower than those for a grass-roots combined-cycle plant. The overall project schedule requires about 34 to 39 months. This is the option that is used most often.

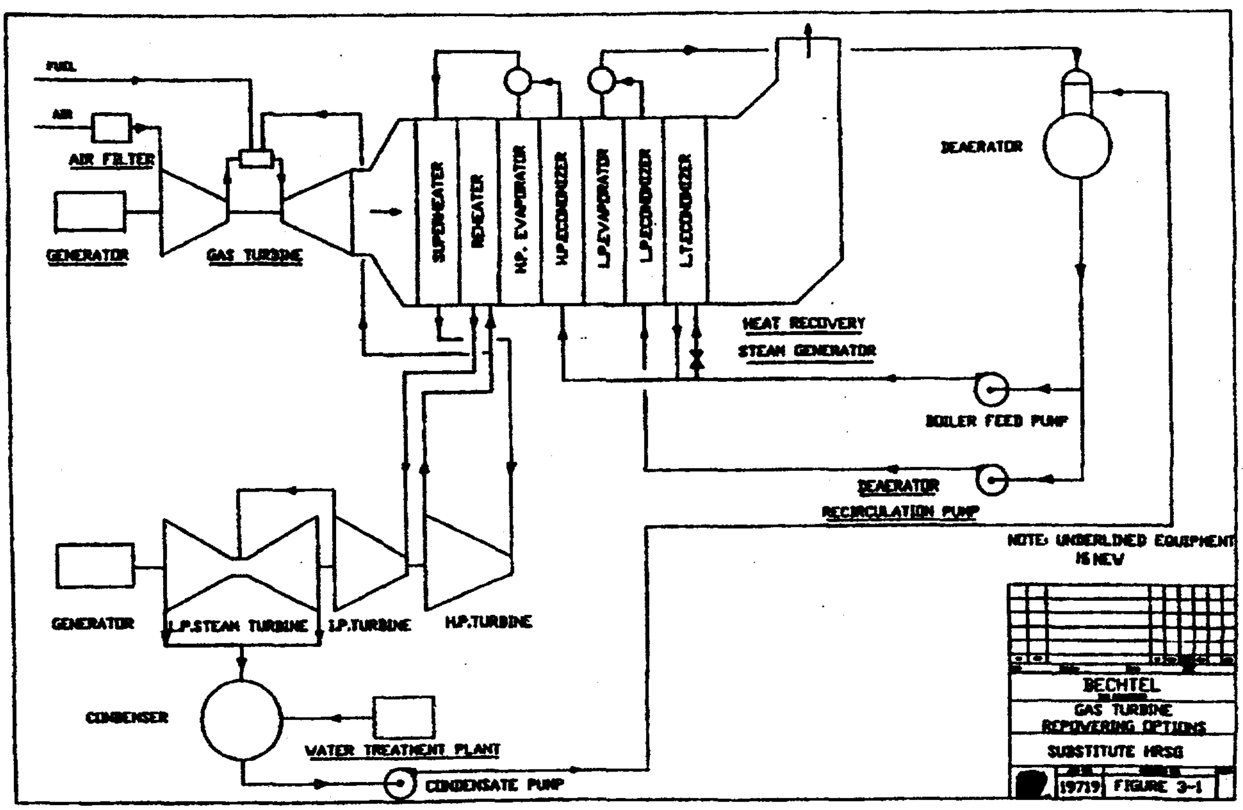

Figure 7. HRSG Substitution.

Supplemental HRSG Repowering

A gas turbine exhausts into a new HRSG which produces superheated steam (Fig. 8). This steam is delivered to the existing boiler at existing steam conditions. Cooled exhaust gases are discharged into the windbox of the existing boiler. Major new generation equipment includes the gas turbine generator, HRSG, steam air preheater, and stack gas cooler. This option has the potential to increase plant output by 35 to 70 percent and plant efficiency by 5 to 15 percent. Emissions on a per kW basis are lowered. Capital costs on a per kW basis are estimated to be lower than those for substitute HRSG repowering. The overall project schedule requires about 34 to 39 months. Typically, this option presents a high level of technical uncertainty because of the major modifications to the existing boiler.

Hot Windbox Repowering

The gas turbine exhausts go directly into the windbox of the existing boiler (Fig. 9). This option is similar to supplemental HRSG repowering except that there is no HRSG to cool the exhaust gases. Major new generation equipment include the gas turbine generator, stack gas cooler, and steam air heater. It has the potential to increase plant output by 30 to 50 percent and plant efficiency by 5 to 10 percent. Emissions on a per kW basis are lowered. The capital costs and project schedule are the same as those for supplemental HRSG repowering.

Feedwater Heating Repowering

The gas turbine exhausts go directly into a recuperative feedwater heater where all or some of the feedwater for the existing boiler is heated (Fig. 10). Cooled exhaust gases are vented to the atmosphere. The steam plant remains essentially the same except for the relocation of some feedwater heaters on the discharge side of the boiler feed pumps. Major new generation equipment includes the gas turbine generator and recuperative feedwater heater. This option has the potential to increase plant output by 20 to 30 percent and plant efficiency by 2 to 5 percent. This option may increase total plant emissions. Capital costs are typically low compared to all other repowering options. The typical overall project schedule requires about 30 to 33 months. This option is rarely used because of its low efficiency gain.

Station Repowering

Installation of a gas turbine or a combined-cycle plant at an existing plant site without using any existing power generation equipment is called station repowering (Fig. 11). Its performance is similar to that of substitute HRSG repowering. The station output is limited only by regulatory requirements and utility needs. Since some of the existing plant infrastructure can be retained, the capital cost is typically lower than that for a grass-roots combined-cycle plant. The plant schedule is similar to that for substitute HRSG repowering.

Repowering uses proven generation technology. Its major technical risks are associated with the use of old existing equipment. Therefore, repowering requires a thorough evaluation of existing equipment conditions and performances and an assessment of required repair and refurbishment for this equipment to minimize these risks.

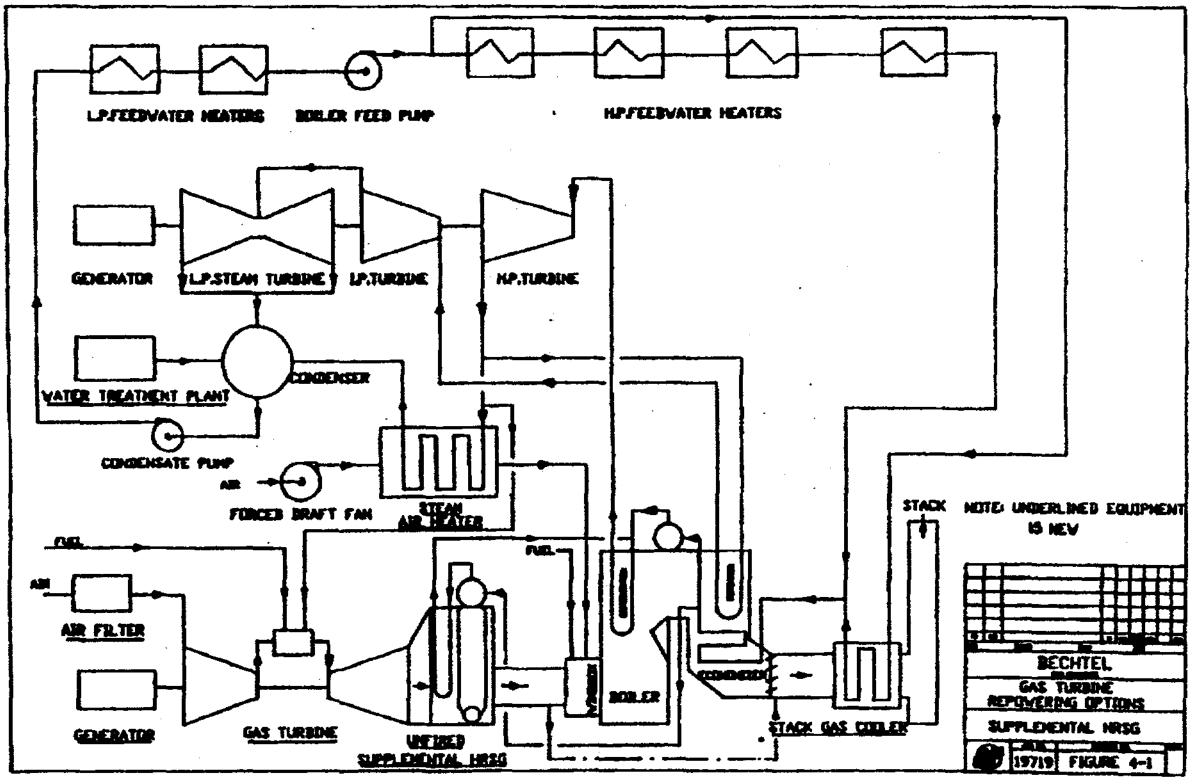

Figure 8. Supplemental HRSG.

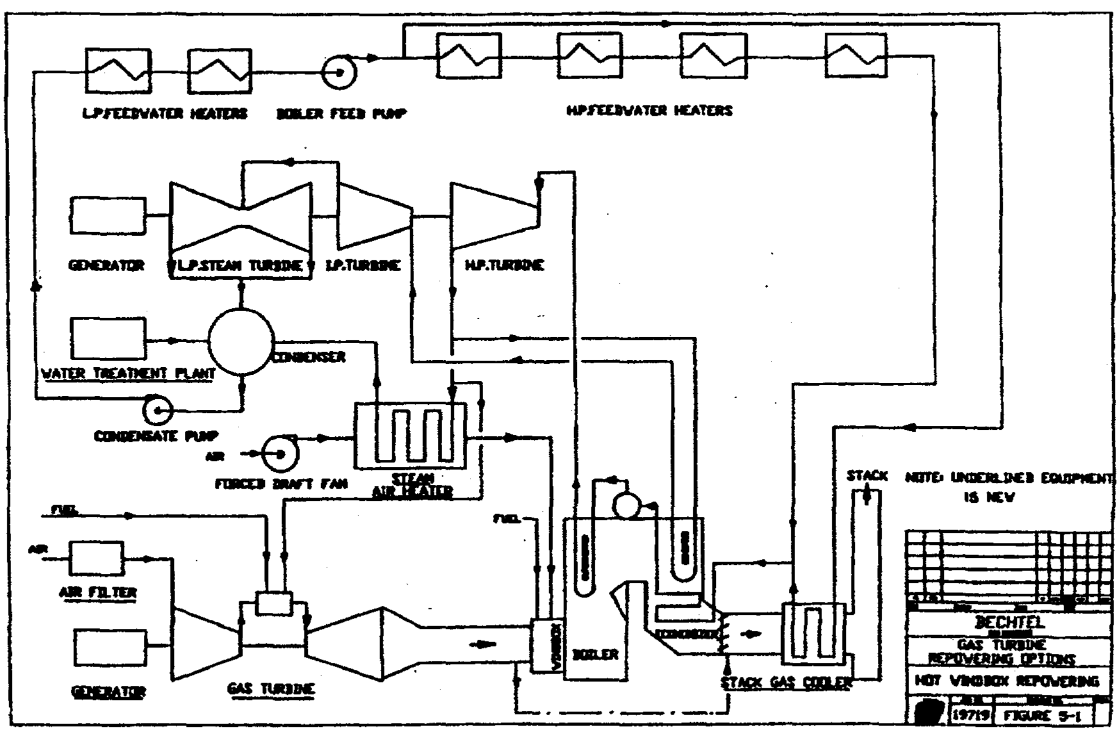

Figure 9. Hot Windbox.

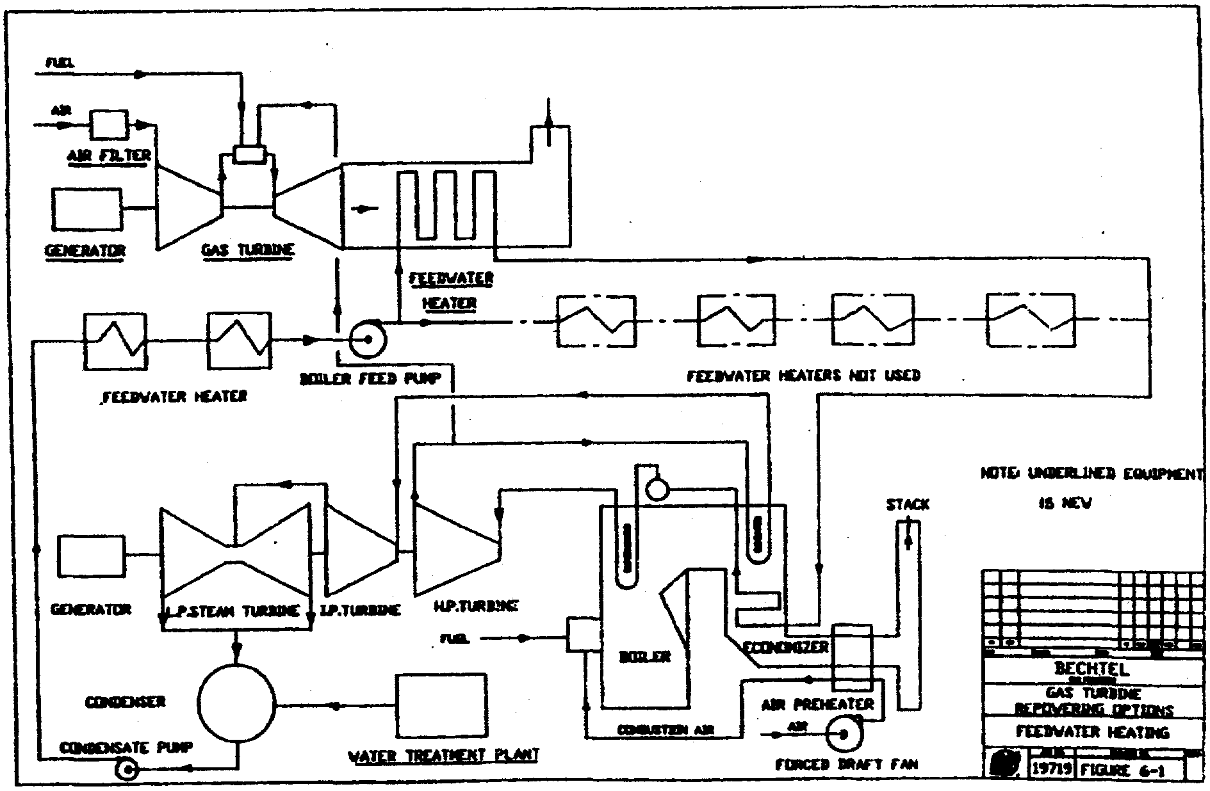

Figure 10. Feedwater Heating.

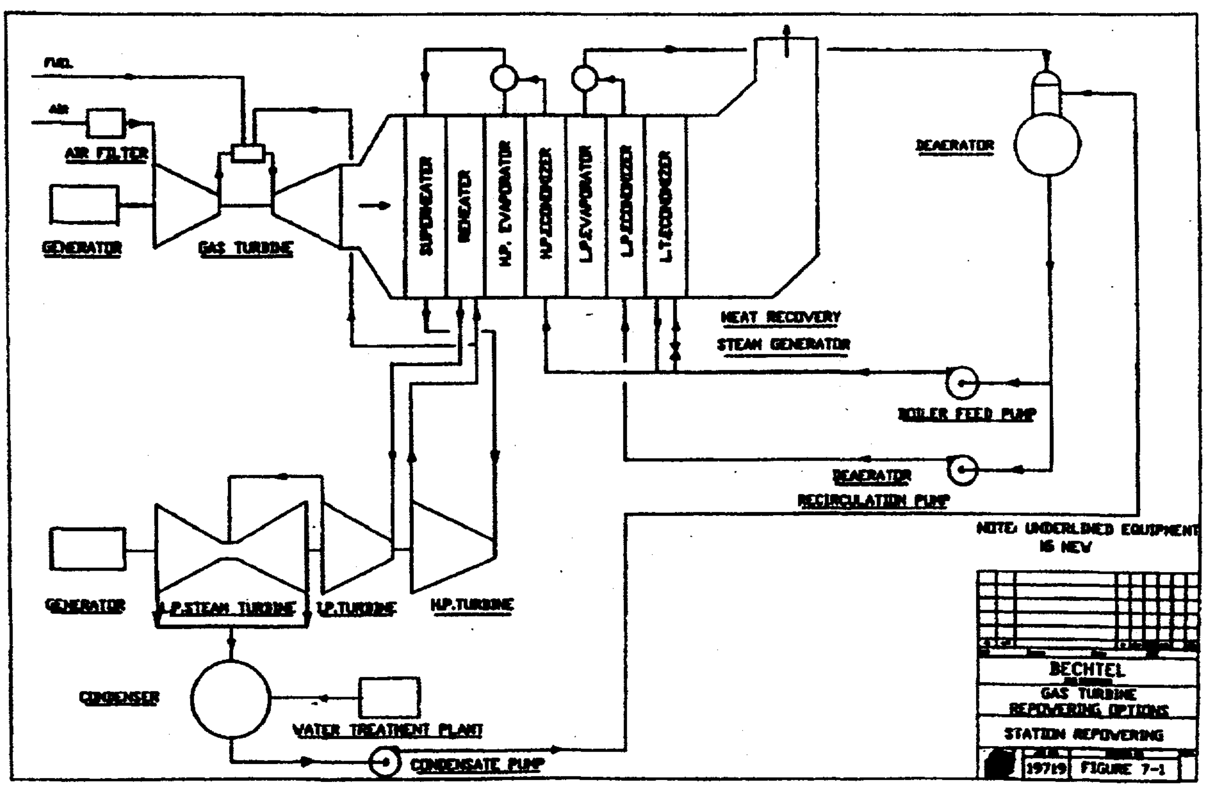

Figure 11. Station Repowering.

FT4000 IC/Repowering

Repowering of existing steam cycle equipment with aero-derivative engines offers a potential first step toward achieving the HIPPS program goal of replacing natural gas with coal in high-performance power generating systems while using currently available technology. Since there was no site-specific data on repowering, the approach used to make a preliminary assessment of this application was to identify the range of sizes and steam conditions that could be handled by one FT4000 IC (or one FT4000 IC-based HAT engine). This was done by defining the largest size, or "base," repowering system, the one that used all the GT exhaust as combustion air. The exhaust was then bypassed around the boiler to HRSG's that actually were used to heat feedwater. In this manner, smaller boilers were identified; the range of sizes that one engine could handle varied from less than 90 MW to over 220 MW.

The FT4000 IC is a high pressure ratio, intercooled gas turbine having a high simple cycle efficiency (>41% HHV) and is well suited to provide preheated air to a coal fired boiler as shown schematically in Fig. 12. The key part of the system shown in Fig. 12 is the gas turbine combustion air (HPC discharge air) convective preheater which makes it possible to utilize a portion of the coal heat in the gas turbine cycle. This preheater, in effect, takes the place of a regenerative heat exchanger that would be used with a conventional regenerative gas turbine cycle. In the case of the FT4000 IC, the high pressure ratio design does not produce an exhaust temperature high enough to make the use of a regenerator attractive (except for the Humid Air Turbine (HAT) cycle). The exhaust temperature of approximately 740°F, however, makes it ideal as the combustion air for a coal fired boiler.

In Fig. 12, it can be seen that the boiler is assumed to be of conventional design in regard to steam generation, superheat and reheat provisions. The absence of a regenerative air preheater allows the exhaust to be used for feedwater heating and eliminates the need for extraction heaters. The gas turbine combustion air heater (referred to as the convective heat exchanger in the HITAF system) has a design HITAF exhaust stream inlet temperature of 1800°F. This temperature was selected for the HITAF system since it is ideal for non-catalytic NO_x reduction and would permit reasonable operating times between removal of deposits to avoid densification. This convective heat exchanger would be a prototype for the HITAF system.

To make this concept applicable to existing steam equipment, a flow diverter is included allowing a portion of the gas turbine exhaust to bypass the furnace. That bypass gas is sent to a HRSG where its heat content is used to heat feedwater for the steam cycle. Figure 13 shows the range of steam cycles that can be accommodated by varying the amount of exhaust gas sent to the HRSG. The values considered are intended to cover the range of probable steam conditions that would be encountered in a repowering operation. They range from a relatively high-performance 2400 psi/1050°F/1050°F reheat cycle to a 1250 psi non-reheat cycle. The corresponding efficiencies for each cycle are given in Fig 14 as a function of the fraction of exhaust gas sent to the HRSG. The output for each system includes the gas turbine contribution, which is constant at 108.9 MW for the cases presented. Note that

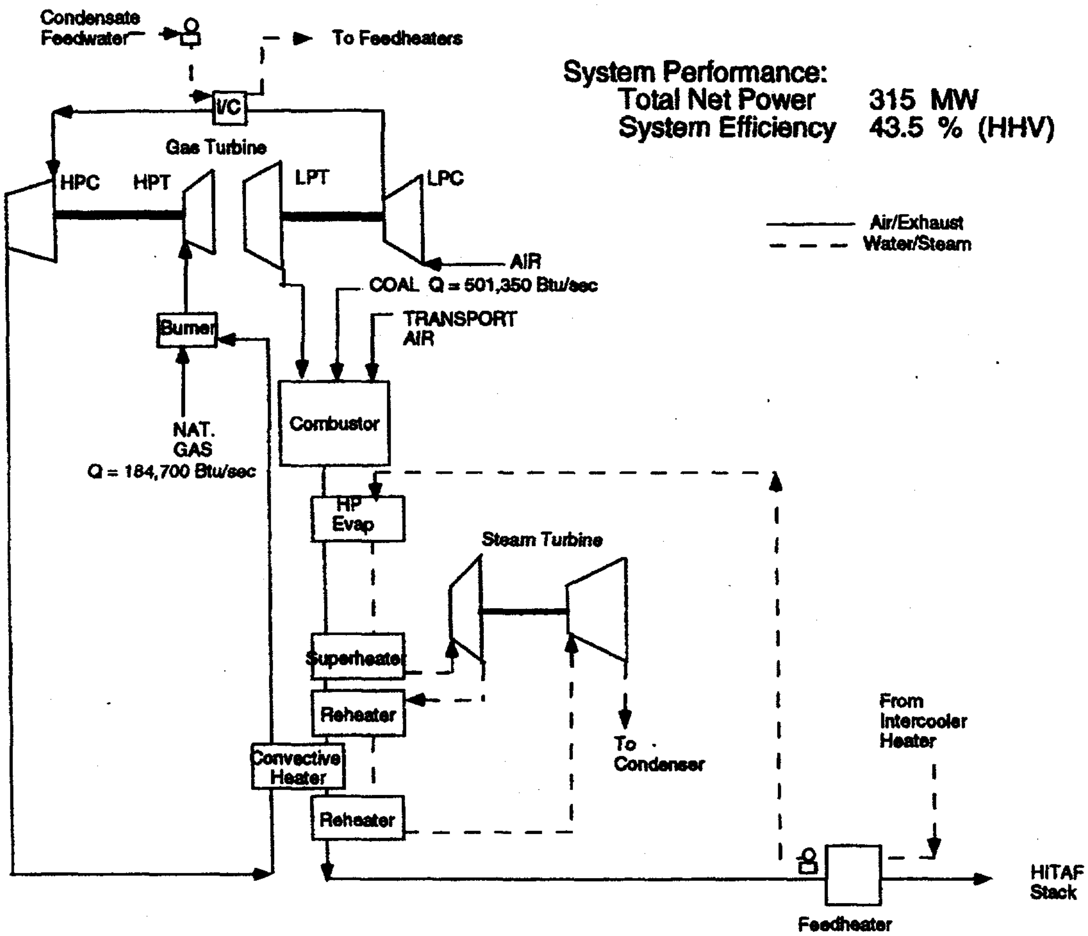

Figure 12. Repowering Configuration FT4000 IC.

the gas turbine output is slightly less than that reported elsewhere for simple cycle operation due to the lower amount of gas required in the burner and, thus, reduced turbine mass flow rate. At the baseline convective air preheat outlet temperature of 1300°F, the heat required to achieve the 2700°F firing temperature is reduced by approximately 25%. This forms the basis for the desirability of the cycle which is the reduction of natural gas consumption and its replacement by coal utilization.

As the fraction of exhaust gas sent to the HRSG is increased, the system would be expected to approach a normal combined cycle in appearance. This occurs because the fraction of turbine exhaust for boiler combustion air decreases resulting in a decrease of steam cycle output approaching levels that would be expected in combined cycle. However, the low (about 750°F) gas turbine exhaust temperatures will not support the steam temperature levels used here. Thus, there is a practical limit to the bypass fraction both from a thermodynamic as well as steam turbine size standpoint.

In the above analysis, excess air in the coal fired boiler was fixed at 20%. Also fixed was the ratio of 2:1 between transport air (ambient air) and coal. Therefore, the portion of the total heat input provided by methane or natural gas is a direct function of the split in the exhaust between the furnace

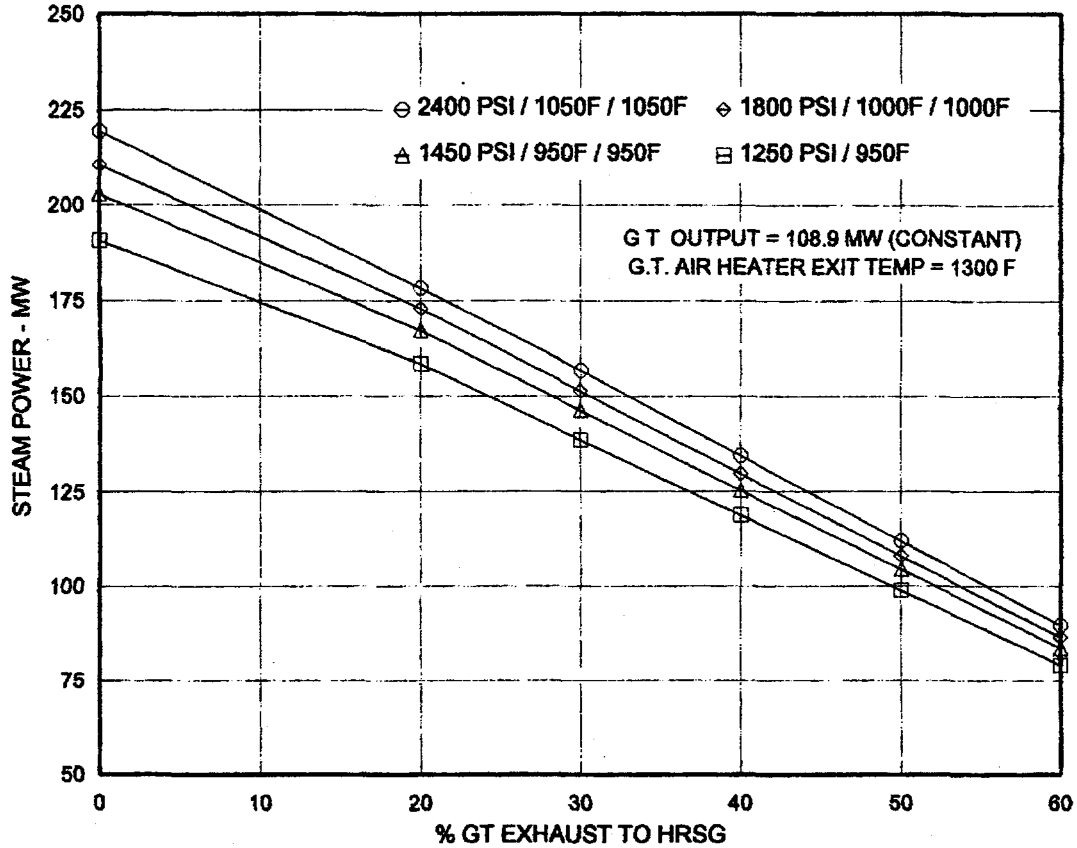

Figure 13. Steam Cycle Output.

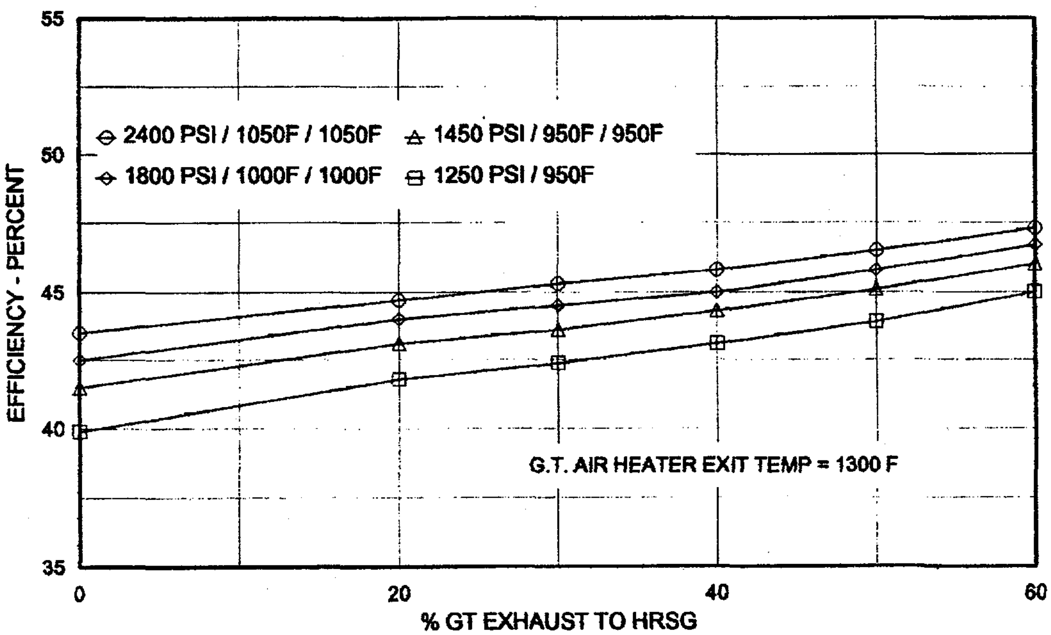

Figure 14. Overall Cycle Efficiency.

and the HRSG. This relation is shown in Fig. 15 for three different combustion air preheat temperatures. The effect of the increased air preheat is discussed later.

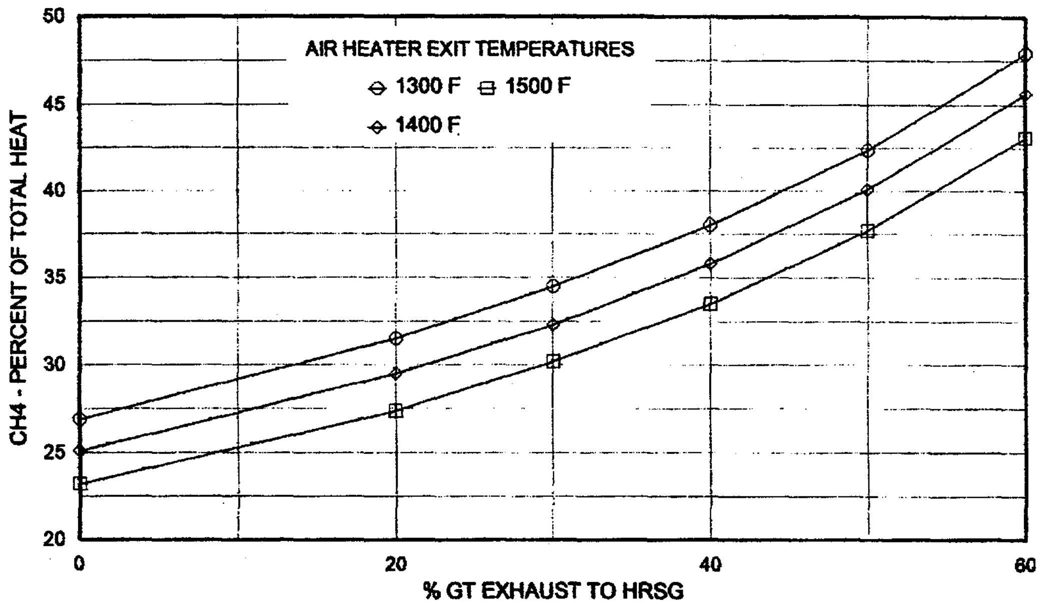

Figure 15. Methane Requirements.

The noticeable change in slope of the curves at 20% exhaust flow to the HRSG results from an excess of low temperature heat as that flow is increased further. The slope change is more noticeable in Fig. 16, discussed below, and is caused by limiting the amount of heat recovered from the gas turbine intercooler to the amount needed to heat the steam feedwater to 225°F. The remainder of the heat in that stream is sent to the cooling tower. This allows a stack temperature of 240°F to be achieved in both exhaust streams. This analytic approach is typical and indicative of the level of detail that has been used in this study.

The primary results indicate that as the fraction of gas turbine exhaust bypassing the boiler is increased, steam power decreases, efficiency increases and so does the fraction of heat from methane. Since the goals of the HIPPS program are stated in terms of efficiency and percent methane, a plot of efficiency as a function of percent methane for the various steam cycles is shown in Fig. 16. That figure shows the obvious advantages to repowering with a high performance steam cycle. It also shows that with such a steam cycle an efficiency in excess of 45% (HHV) is possible and that 47% efficiency can be achieved with 40% of the heat coming from methane. The obvious break in the curves of Fig. 16 is due to the need to change the arrangement of the heat recovery system as steam and, thus, feedwater flow is decreased. At relatively high steam flow rates (less than 20% flow to the HRSG), heat from the gas turbine intercooler can be used to preheat the feedwater prior to entering the economizer, while achieving a 240°F stack temperature. At lower steam rates, all of that heat cannot be utilized and

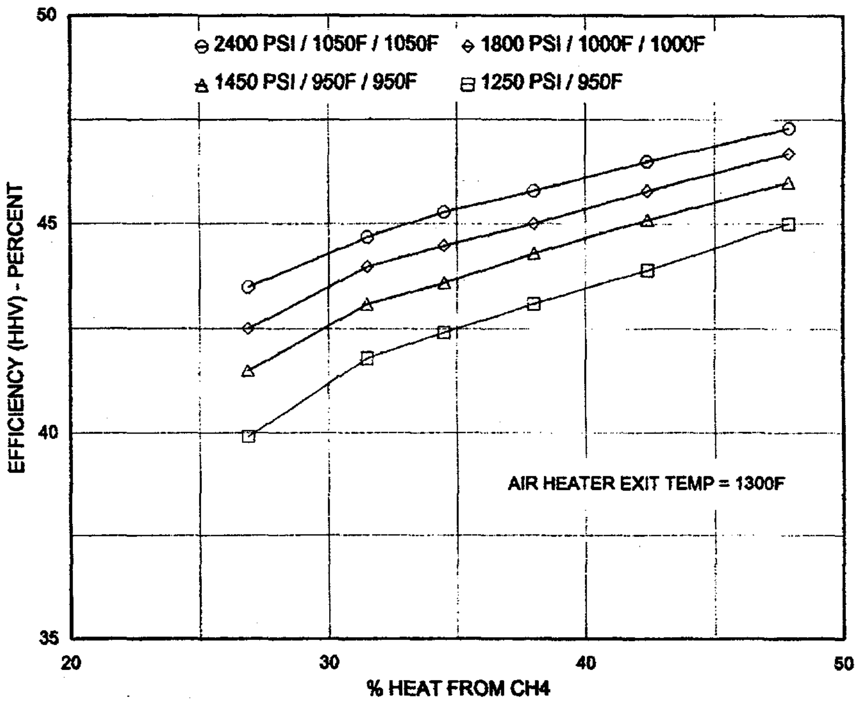

Figure 16. Efficiency as a Function of Methane Fraction.

performance suffers. It is anticipated that, in a specific case, some use would be found or the excess heat would be sent overboard.

In the baseline HITAF cycle, air from the convective heat exchanger is heated further in the radiant section of the furnace. This additional air preheat allows us to reach the performance goal, while burning only 35% methane. For the repowering configuration, increasing the duty of the convective heat exchanger was investigated. For the 2400 psi/1050°F/1050°F steam cycle, the effect of increased air heater exit temperature on steam cycle output is shown in Fig. 17. At full flow to the boiler (no flow to the HRSG), there is virtually no change in steam cycle output as air preheat temperature is increased. This is the result of an increase in oxygen content of the gas turbine exhaust, which allows more coal to be burned making up for the increased duty of the convective exchanger. As gas turbine exhaust flow to the HRSG is increased, the heat required by the convective exchanger becomes a more significant part of the total and steam power drops off somewhat with increased air preheat temperature. It should be noted that there is a slight reduction in gas turbine output as the combustion air preheat temperature is increased. For the 1300°F, 1400°F and 1500°F conditions, the corresponding gas turbine output levels are 108.9 MW, 108.2 MW and 107.4 MW, respectively.

Overall efficiency for the system with the 2400 psi/1050°F/1050°F steam cycle is virtually unchanged, with increased combustion air preheat. However, as was shown in Fig. 15, preheat temperature has a marked effect on the fraction of methane used in the system. The resultant effect on efficiency as a function of the fraction of heat from methane is shown in Fig. 18. There it shows that with an air preheat temperature of 1500°F, an efficiency of 47% can be achieved at a methane use rate of 35%.

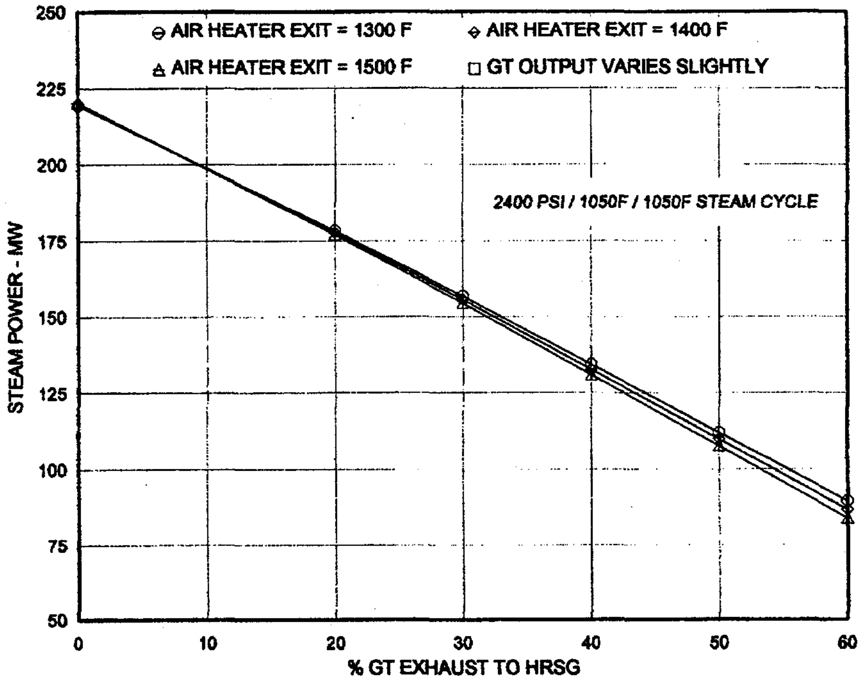

Figure 17. Effect of Air Heater Temperature.

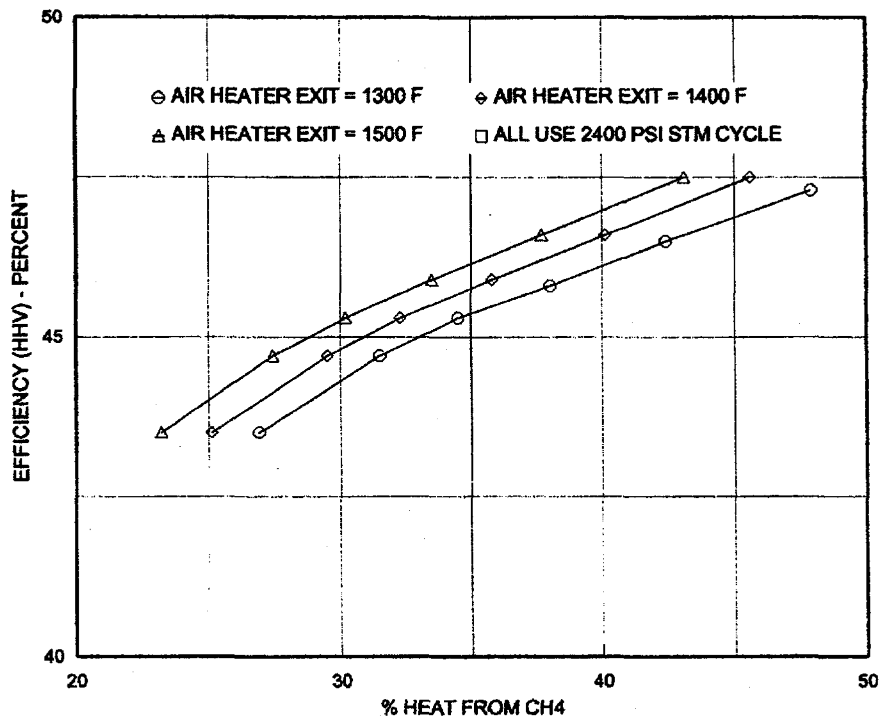

Figure 18. Effect of Methane Fraction.

FT4000 HAT

In principle, repowering with the Humid Air Turbine (HAT) cycle is much the same as with the basic simple cycle FT4000. The system is shown schematically in Fig. 19. Performance at the base point (no GT exhaust bypass) with a 2400 psi/1050°F/1050°F steam cycle is significantly better than for the simple cycle version; 45.9% as compared to 43.5% for the simple cycle. The improvement comes at the expense of a higher methane use fraction. The ratio of methane heat to total heat at the base point is 0.369.

The effect of bypassing a portion of the gas turbine around the coal boiler for use as feedwater heating follows the same trend as the simple cycle with the curves being essentially parallel. This is shown in Fig. 20.

As with the simple cycle repowering, gas turbine exhaust air is used as preheated combustion air in a coal fired boiler. Because the exhaust gas contains a significant amount of water vapor, boiler combustion temperature is reduced both by the effect of less oxygen as a result of combustion in the gas turbine and the added water vapor. Since the resultant combustion process differs from that of conventional boilers, it will be necessary to examine the system to determine what problems will be encountered in achieving a stable flame.

The primary variables that affect flame temperature are degree of saturation as measured by saturator exit temperature, preheat of gas turbine burner inlet air, excess air in the coal furnace and amount of coal transport air. For this study, an excess air level of 20% was assumed and a transport air to coal ratio of 2:1 was used. Adiabatic flame temperatures in the range of 2500 to 2700 F were calculated using dry Illinois #6 coal. The effect of these levels on the combustion process has yet to be investigated, but various means of raising flame temperature and hopefully improving performance have been considered and are discussed later.

The other major difference in using the HAT configuration is the need to cool down the high pressure compressor exhaust and to subsequently add water vapor in the saturator. This cooling is necessary since the HP air would be cooled in passing through the saturator and the sensible heat in that stream would be utilized at a greatly reduced temperature. As shown, that heat is used in the steam cycle economizer. The reduced HP air temperature and increased mass flow rate results in a significant increase in the duty of the HP air convective heat exchanger. In order to maximize temperature differences in the various heat exchangers (and reduce cost), it will likely be necessary to make the convective exchanger in two sections as shown in the schematic.

Heat for the saturation process is provided by bleeds from the steam turbine. This is in marked difference to the conventional combined cycle, where there is an overabundance of low temperature heat. Other arrangements of the bleeds may be found desirable for a particular application but this provided the simplest schematic arrangement for this study. It should be noted that the integration of

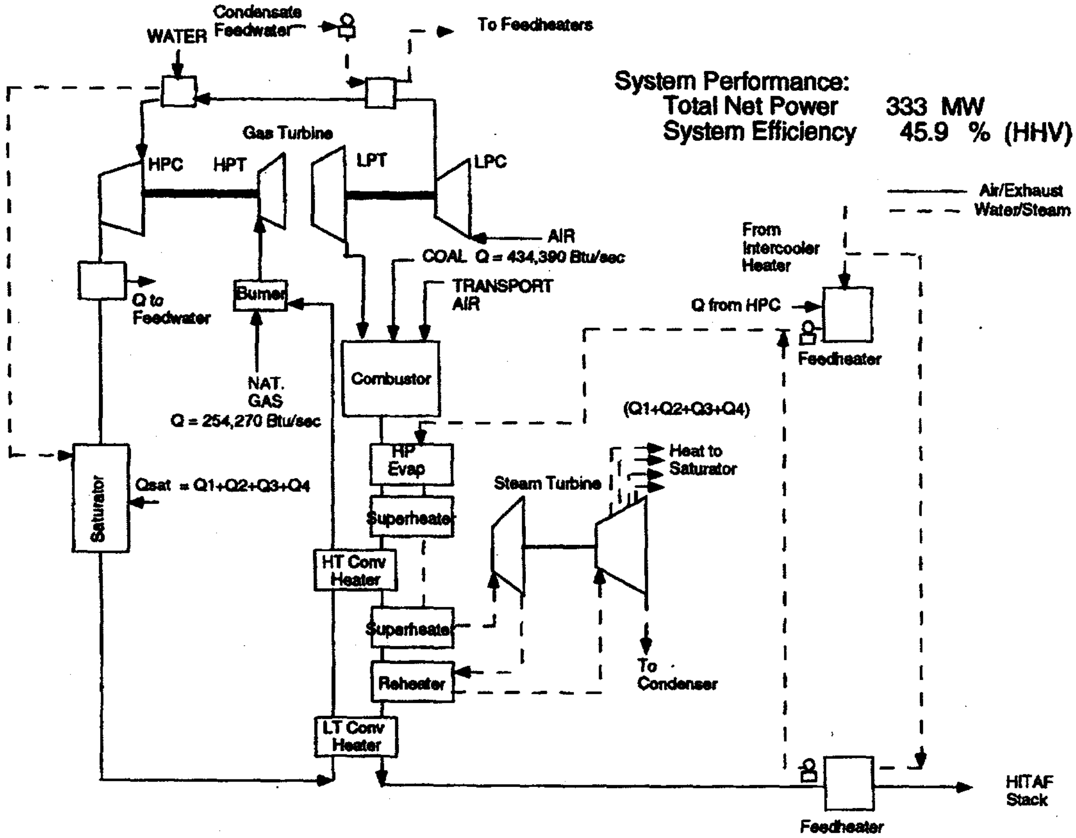

Figure 19. Repowering Configuration FT4000 HAT.

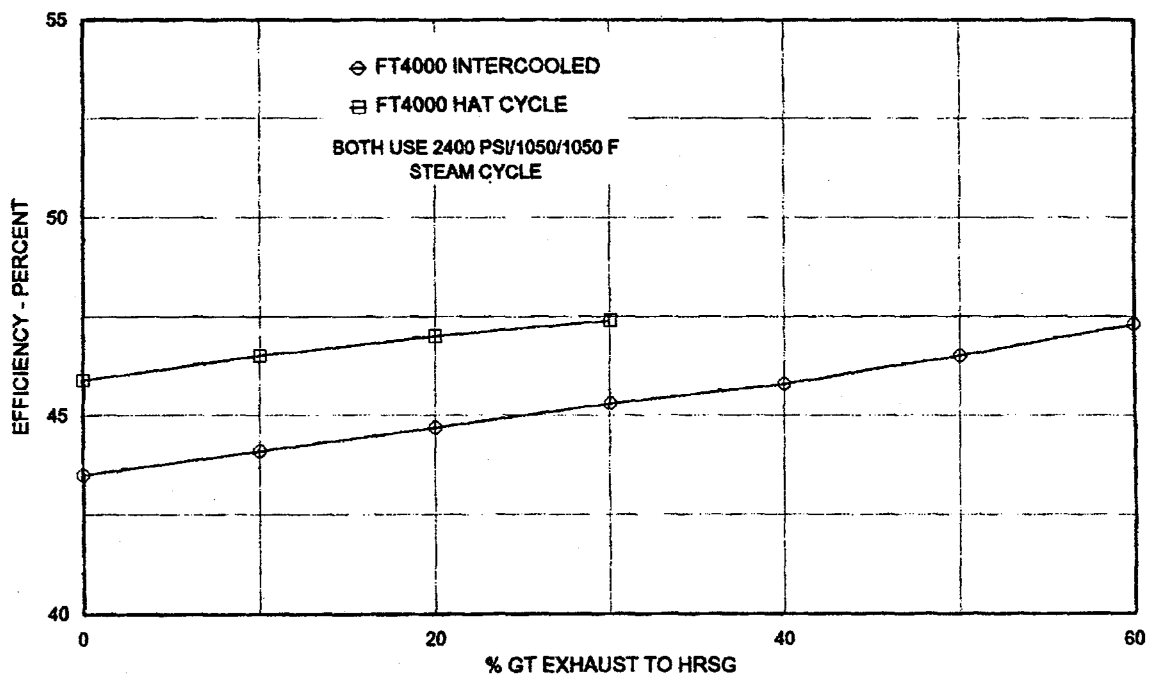

Figure 20. Comparison of Efficiencies.

the HAT, HITAF and steam bottoming cycles has the additional benefit of eliminating the need for the air-to-air regenerative heat exchanger which is usually quite large to maintain efficiency. Here the reheating of the HP air stream can be done with relatively large temperature differentials. The low temperature exhaust heat can be recovered by the steam cycle feedwater which results in a much smaller heat exchanger.

A number of other things concerning the system are worth noting. The large amount of heat required to reheat the compressor discharge after being saturated reduces the high temperature heat available for the steam cycle. Also, the water vapor in the air requires more methane to be burned to achieve the desired turbine inlet temperature, further depleting oxygen. As a result, less coal can be burned at the base condition when all of the exhaust is sent to the boiler. At the zero bypass condition, the fraction of total heat provided by methane is approximately 37% as compared to 27% for the FT4000 IC/HITAF cycle. The HAT cycle shows a less marked advantage, when compared to the intercooled cycle in terms of efficiency versus methane fraction as is shown in Fig 21. The HAT cycle system experiences an excess of low temperature heat as the amount of gas turbine exhaust bypassed around the boiler exceeds approximately 26%.

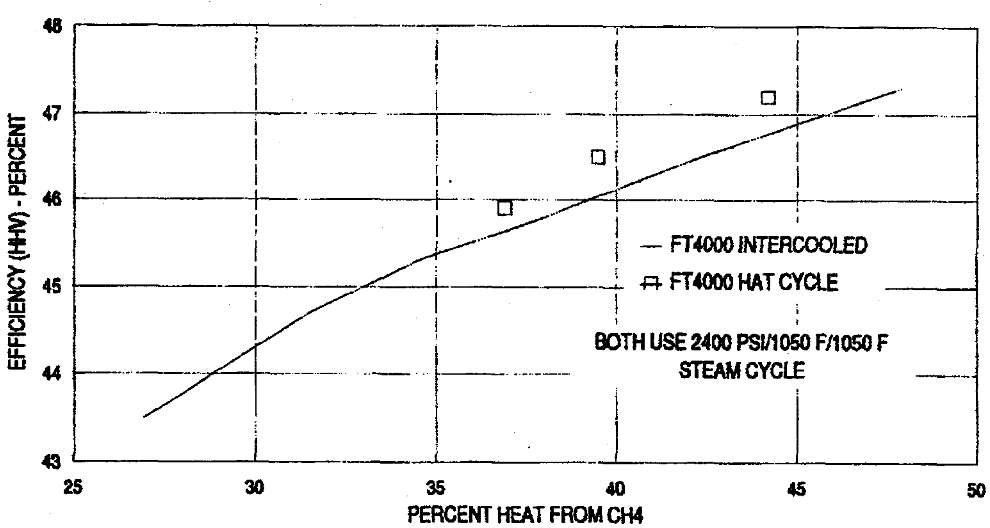

Figure 21. Efficiency as a Function of Methane Fraction.

The results of parametric variations and alternative schematic arrangements are worth noting. Raising the temperature of the high pressure air out of the convective heat exchanger has little effect on performance but does reduce the methane ratio. That ratio becomes 0.35 at 1350°F and 0.338 at 1400°F out of the heat exchanger. Also noted was that some of the uses of low temperature heat, such as for pre-heating the methane, do not appear to be beneficial in this cycle.

A number of methods of raising the coal flame temperature have been considered, but have not as yet been fully investigated. There are three primary factors that affect flame temperature. The first, temperature of the combustion air has a direct effect and could be improved to a limited extent by further pre-heating. The others, oxygen partial pressure and water vapor content are closely related and are affected by other parameters such as high-pressure air preheat, saturator exit temperature, and gas turbine firing temperature. The latter is fixed for the purposes of this study but the others have been investigated.

An increase in air pre-heat temperature of 100°F produces an increase of approximately 50°F in flame temperature due to reduced methane combustion. This is desirable since it also decreases the methane ratio while performance remains unchanged. Reduction of the saturator exit temperature has a similar effect, resulting in less methane being burned. A 10°F reduction in saturation temperature produces an 80°F increase in combustion temperature, while reducing efficiency by 0.15 percentage points.

Other approaches also have been considered. In particular, cooling of the exhaust against a non-vitiated combustion air stream could provide a greater degree of flexibility to accommodate a larger range of steam cycles, while improving system performance. As a rough estimate, the gas turbine exhaust contains 10% oxygen by volume. Using one half of that stream to pre-heat combustion air would permit the same amount of coal to be burned and should result in a reduced stack loss, higher availability due to increased firing temperature, and permit the other half of the stream to provide low-temperature heat.

To fully evaluate the HAT cycle, several additional things need to be done: simulation of a water loop; and revisiting the simulation of the mass transfer saturator. It appears that there are some aspects of that system that are sufficiently different from the typical combined cycle to leave room for further improvement. In both the simple and HAT cycles, it appears that the use of bleed steam for feed heating could improve performance at the base case. These things are at the next level of detail that will be included in Phase II analyses.

Preliminary Economics for Repowering

A high-level preliminary analysis was carries out to identify the relative economics of HITAF repowering. The FT4000 IC/HITAF and the HAT/HITAF were compared to the two most likely alternative repowering schemes; aero-derivative (nominal 110 MW) and heavy frame (nominal 185 MW) machines used in the HRSG substitution mode (Fig. 7). Performance and costs for the equipment were obtained from several yet unreleased reports by Fluor Daniel and from Bechtel reports. The costs were escalated to same year costs (1994). It was assumed that the plant infrastructure and steam turbine/generator and water systems were unchanged in all cases. The plant to be repowered was a 1800 psi/950°F/950°F, 200 MW system, a size that could be repowered by a FT4000 IC using turbine exhaust as the coal-fired boiler combustion air.

Both the aero-derivative and the heavy frame machine required supplemental firing (gas) to generate enough steam for a 200 MW plant. Costs for gas were assumed to be roughly those used in the 1993 EPRI TAG®, i.e., current cost for gas was twice that for coal and the 10-year future cost was four times.

The cost of electricity was determined using the 10-year levelizing factors in the EPRI TAG®. The levelized cost of electricity (LCOE) for the FT4000 IC was used to normalize all the costs. (The LCOE for the aero/HITAF using current fuel prices was unity.) The results are shown in Fig. 22. At current and projected fuel prices, the HAT/HITAF has the lowest LCOE. This is because of it's projected lower capital and operating costs. As would be anticipated at current fuel prices, both the aero/HRSG and the heavy frame/HRSG are projected to have lower LCOE's. This is mostly due to their lower capital costs. Their higher efficiencies are obtained on a more costly gas fuel, and as the gas/coal cost ratio increases in future years, their higher operating costs make them less attractive versus the HITAF configurations.

Because of the higher efficiencies possible with the FT4000 IC with bypass flow to HRSG's (feedwater heating), LCOE's for this configuration were developed and are shown in Fig. 23. The savings due to higher efficiencies were offset to some extent by the increased cost ($/kW) of the smaller boiler and the cost of the HRSG. Nonetheless, a 5% lower LCOE could be realized in the maximum bypass case.

Concluding Remarks

The use of the aero-derivative engine with the HITAF offers higher efficiencies and potentially lower capital costs, in HAT configuration, than realizable with heavy frame machines. The technology advancements in materials and cooling techniques developed for aircraft engines shows up more quickly, giving the aero-derivative engine even more of a potential advantage in the future.

When used in repowering, these engines could add as much as 10 or 12 points (around 30-35%) to the efficiencies of older steam stations. The repowering configurations do not have to use the radiative heat exchangers, somewhat simplifying the HITAF, and should result in systems having lower overall cost of electricity than current repowering alternatives. These advantages are realizable with coal providing 60-70% of the cycle input heat requirement.

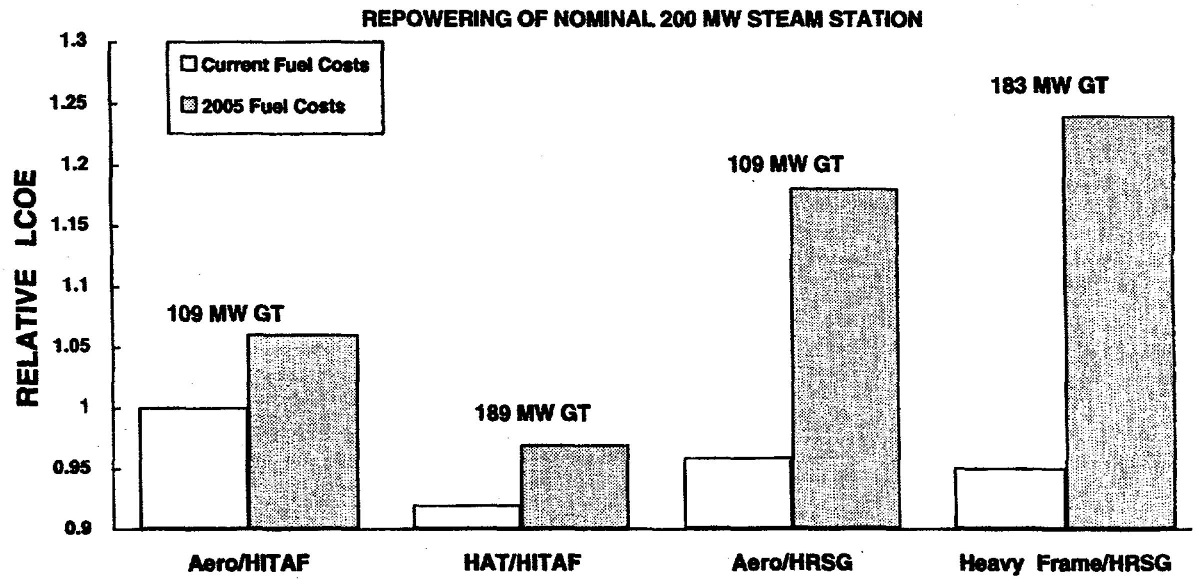

Figure 22. Relative LCOE.

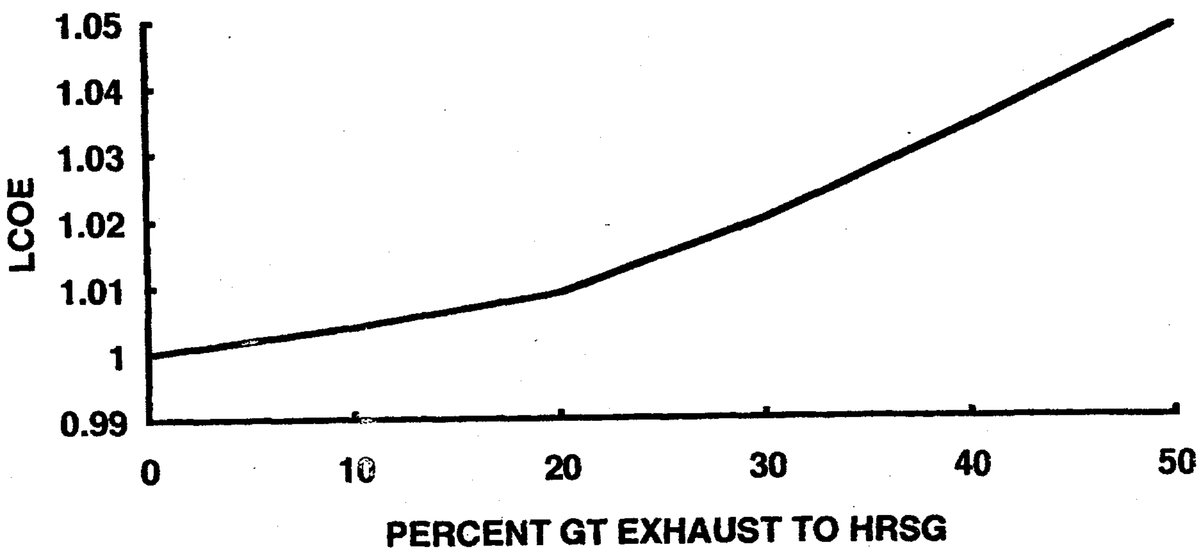

Figure 23. LCOE as a Function of Exhaust Bypass.