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Advanced Aeroderivative Gas Turbines in Coal-Based High Performance Power Systems (HIPPS)

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Abstract

The Department of Energy's Federal Energy Technology Center (FETC) is sponsoring the Combustion 2000 Program aimed at introducing clean and more efficient advanced technology coal-based power systems in the early 21st century. As part of this program, the United Technologies Research Center has assembled e seven member team to identify and develop the technology for a High Performance Power Systems (HIPPS) that will provide in the near term, 47% efficiency (HHV), and meet emission goals only one-tenth of current New Source Performance Standards for coal-fired power plants. In addition, the team is identifying advanced technologies that could result in HIPPS with efficiencies approaching 55% (HHV).

The HIPPS is a combined cycle that uses a coal-fired High Temperature Advanced Furnace (HITAF) to preheat compressor discharge air in both convective and radiant heaters. The heated air is then sent to the gas turbine where additional fuel, either natural gas or distillate, is burned to raise the temperature to the levels of modern gas turbines. Steam is raised in the HITAF and in a Heat Recovery Steam Generator for the steam bottoming cycle. With state-of-the-art frame type gas turbines, the efficiency goal of 47% is met in a system with more than two-thirds of the heat input furnished by coal. By using advanced aeroderivative engine technology, HIPPS in combined-cycle and Humid Air Turbine (HAT) cycle configurations could result in efficiencies of over 50% and could approach 55%.

The following paper contains descriptions of the HIPPS concept including the HITAF and heat exchangers, and of the various gas turbine configurations. Projections of HIPPS performance, emissions including significant reduction in greenhouse gases are given. Application of HIPPS to repowering is discussed.

Introduction

In his Fiscal 1997 Performance Agreement with the President (Peña, 1997) Secretary of Energy Federico Peña stated that one of DoE's major goals is to "Provide the nation's electric power industry from 2000 to 2010 with a new generation of natural gas, biomass and coal power technologies that progressively reduce CO2 emissions by 30 to 50 percent, lower SO2 and NOx emissions to as little as 1/10th of the levels mandated by current Federal standards, and produce electricity at costs 10 to 20 percent below today's conventional plants." A key part of this ambitious plan is the Combustion 2000 Program which has as a component the High Performance Power Systems (HIPPS). HIPPS is a multi-year, multi-phase program aimed at developing and demonstrating the technology for an Indirectly Fired Cycle (IFC) based on an advanced technology coal-fired furnace providing preheated combustion air and steam for high performance combined cycles. The specific goals for the HIPPS program are shown in Table 1.

HIPPS Goals		NSPS
Pollutant Emissions		
NOx (lb NO2/MMBtu fuel)	0.06	0.6
SOx (lb SO2/MMBtu fuel)	0.06	0.6
Particulates (lb/MMBtu fuel)	0.003	0.03
Thermal efficiency (HHV) ≥ 47%		
All solid wastes benign		
Coal must be ≥ 65% total fuel (path to 95% coal)		
COE ≤ 90% present cost for NSPS plant		

NSPS - New Source Performance Standards

Table 1 DoE Goals for HIPPS

To achieve these ambitious goals, the United Technologies Research Center put together a seven member team (Table 2) which began the Phase II plant design and component development effort in mid-1996.

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Team Member	Responsibilities
UTRC	Program Management and Integration Air Heater Designs and Materials Duct Heater
Pratt & Whitney	Gas Turbine Design
PSI Technology	Ash Management
University of Utah	Combustor Design
University of North Dakota Energy & Environmental Center	Ash Deposits, Air Heater Testing
Bechtel Group	Commercial Plant Design, BOP
ABB-Combustion Engineering	Subsystem & Prototype Testing, Commercialization
kraftWork Systems, Inc.	Power Systems Analysis
Fluor Daniel	Power Island Design

Table 2 - HIPPS Team Members

A simplified diagram of the HIPPS concept is shown in Fig. 1. The HIPPS differs from the conventional combined cycle in that the compressor discharge air is sent to the coal-fired High Temperature Advanced Furnace (HITAF) shown in Fig. 2, where it is preheated first in a convective air heater (CAH) and then in a radiant air heater (RAH) to approximately 925 C(1700F).

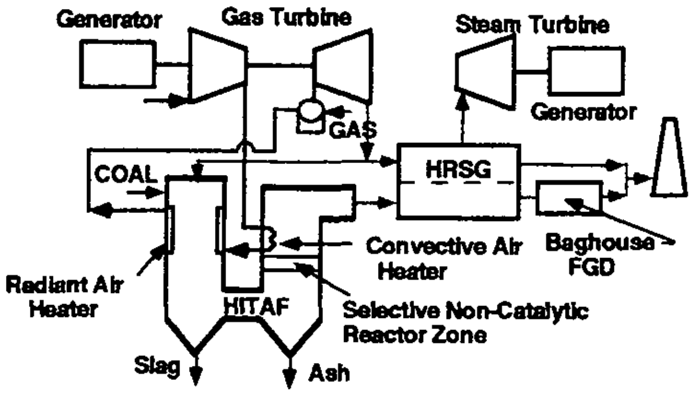

Fig. 1 - Simplified HIPPS

The preheated air then goes to a special combustor where natural gas (or distillate) is use to bring it to the desired temperature (1370 C/2500 F). There are two options for the turbine exhaust: it can be split for use as preheated combustion air for the HITAF with the remainder going to an heat recovery steam generator (HRSG) as shown in Fig. 1; or the entire flow can go to an HRSG. The choice is based on customer preference. The exhaust from the HITAF is sent to a cleanup system consisting of particulate removal and desulphurization and, if needed, deNOx. This system, labeled Baghouse FGD in Fig. 1, uses technologies being developed in other DoE programs such as the Low Emissions Boiler portion of Combustion 2000.

A commercial plant design (Robson and Seery, 1994) has been defined based on the use of a nominal 160 MW frame-type machine having a total combined-cycle plant output of nearly 300 MW at a net efficiency of 47.3% (HHV).

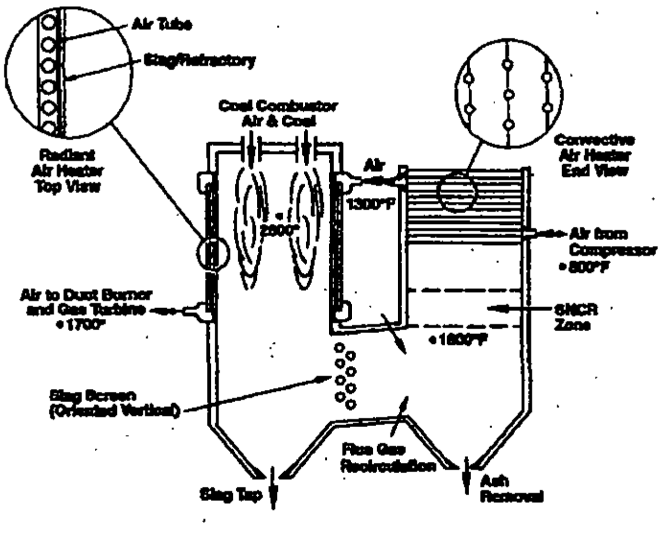

Fig. 2 - High Temperature Advanced Furnace

Aeroderivative HIPPS

At about the same time as the HIPPS program was initiated, two programs on advanced gas turbines were started. The Department of Energy undertook the Advanced Turbine Systems (ATS) program. The objective of the ATS program was to identify an advanced engine fueled by natural gas that would form the basis of a power cycle(s) having an efficiency of 60% (LHV) or better. In the other program, a group of U.S. and European utilities and utility research organizations such as the Electric Power Research Institute (EPRI) and the Gas Research Institute (GRI) formed the Collaborative Advanced Gas Turbine (CAGT) consortium. This consortium sponsored a study on adapting the new generation of high thrust aircraft engines to industrial use.

Aircraft engines such as the General Electric Company's GE90, the Pratt & Whitney PW4000, and the Rolls Royce Trent have thrust ratings approaching 100,000 lb. By replacing the high bypass ratio fan stages with compressor stages and suitably reworking the turbine, simple cycle engines of approximately 50 MW could be envisioned. The addition of intercooling could essentially double the output. Considerable interest in the Intercooled Aero Derivative (ICAD) engine has resulted from these efforts (e.g., Davidson and Hay, 1996)

As part of both the CAGT study and Phase I of the ATS Program, United Technologies conceptualized an intercooled version of the PW4000 as the basis of advanced power cycles (e.g., Robson, 1993). Referred to as the FT4000 IC, this version used airfoil materials, coatings, and cooling techniques being demonstrated in advanced commercial and military aircraft turbine engines to achieve projected nominal outputs of about 125

MW and simple-cycle efficiencies over 45% (LHV on gaseous fuel; the HHV efficiency would be some 9% less). In combined cycle configuration, efficiencies of near 55% (LHV) could be projected, and when used in a Humid Air Turbine (HAT) Cycle configuration, outputs of over 200 MW with efficiencies approaching 61% (LHV) were estimated. A reheat HAT cycle was projected to have net efficiencies of nearly 63% (LHV). This advanced technology ICAD engine was then applied to 21st century versions of HIPPS.

HIPPS/ICAD

The first HIPPS/ICAD configuration considered was a direct comparison to the heavy frame commercial plant design developed in the Phase I part of the Combustion 2000 study. It was limited to 1370 C/2500 F turbine operating temperature and used the conventional steam bottoming cycle of the commercial plant design, 165 bar/ 565 C/565 C (2400 psi/1050 F/1050 F). This configuration, shown in Fig. 3, had an efficiency of 48. 5% (HHV) and a nominal output of 245 MW. The performance of this "current" technology HIPPS/ICAD was somewhat better than the heavy frame machine, due mostly to better turbomachinery efficiencies and a closer match of the exhaust heat from the turbine with the HITAF requirements. The cooling and materials for this potential first generation engine would be similar to those used in the latest versions of heavy frame machines; e.g., the Siemens V84.3a (Becker et al., 1995).

As was the case with the heavy frame machine, this performance is somewhat less (approximately 3%) than could be anticipated from a gas-fired combined cycle using the technology. This is because of the requirement to meet the DoE goal of 65% coal use.

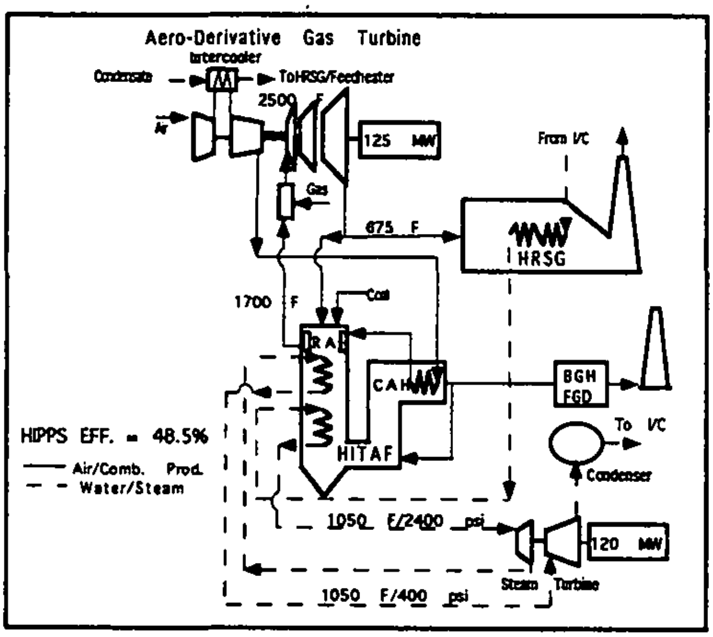

Fig. 3 - Initial HIPPS/ICAD Configuration

The amount of heat from coal that can be transferred to the gas turbine is limited by the heat exchanger materials; i.e., the outlet temperature of the HITAF radiator in the initial commercial configuration is limited to 925 C/1700 F. The remainder of the coal heat goes into steam for the combined cycle. To meet the 65% coal requirement, more steam is raised than is thermodynamically optimum. One way to minimize this efficiency loss is to improve steam cycle efficiency by increasing steam conditions.

In addition to technology advances in gas turbines, the DoE and others such as EPRI have been pursuing steam turbine technology Turbines operating at temperatures up to 815 C (1500 F) and pressures over 415 bar (6000 psi) have been demonstrated by Solar Turbine and its spin-off, Innovative Steam Technologies (Valenti, 1996). These advances have been incorporated into the HIPPS/ICAD; first with the "current" technology version (Fig. 4) and then with the advanced technology reheat version mentioned previously (Fig. 5).

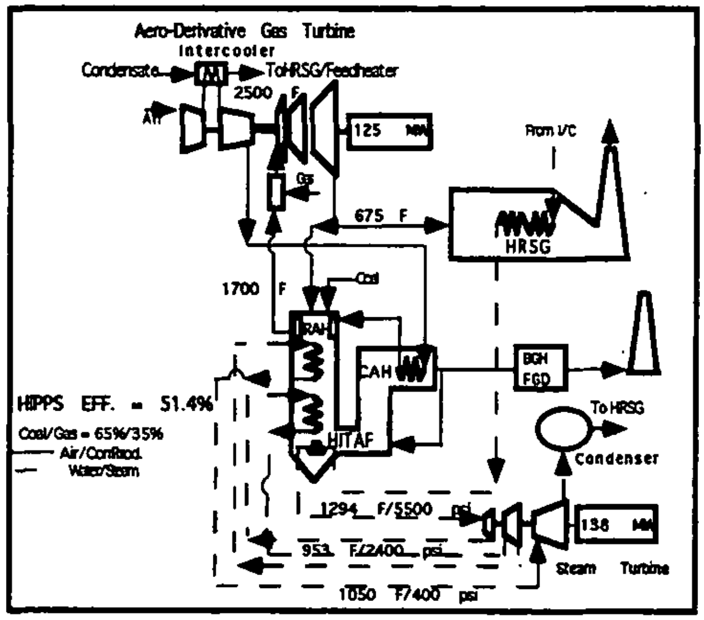

Fig. 4 - HIPPS/ICAD with advanced steam turbine technology

In the Fig. 4 configuration, the advanced steam turbine operating at 700 C (1290 F) and nearly 380 bar (5500 psi) exhausts into the 165 bar machine at 510 C. This results in a performance gain of nearly three points to an estimated overall plant efficiency of 51.4% (HHV).

A much more advanced gas turbine is used in the Fig. 5 configuration. The advances used in this version are those that will appear in commercial flight engines over the next decade and will be used in the later generation (circa 2010+) aero-derivative industrial turbines. The appeareance of this technology could be accelerated through ATS-like development programs for mid-sized gas turbines. This future cooling technology, currently being demonstrated in advanced military engines, indicates that air cooling can be used at rotor inlet temperatures 220 C (400 F) or more higher than current levels. When combined with advances in material technology for base alloys and coatings, aeroderivative engines can be identified that would operate in baseload utility application for 100,000 hr with only 50 blade failures in 1000 engines (Robson, 1993)

With the advanced cooling techniques and materials, this reheat turbine would operate at 1595 C (2900 F) with a pressure ratio around 50. When coupled with the advanced steam system, the overall efficiency approaches 53% (HHV). In all of these cycles, more than half of the heat used in the gas turbine is from the combustion of coal.

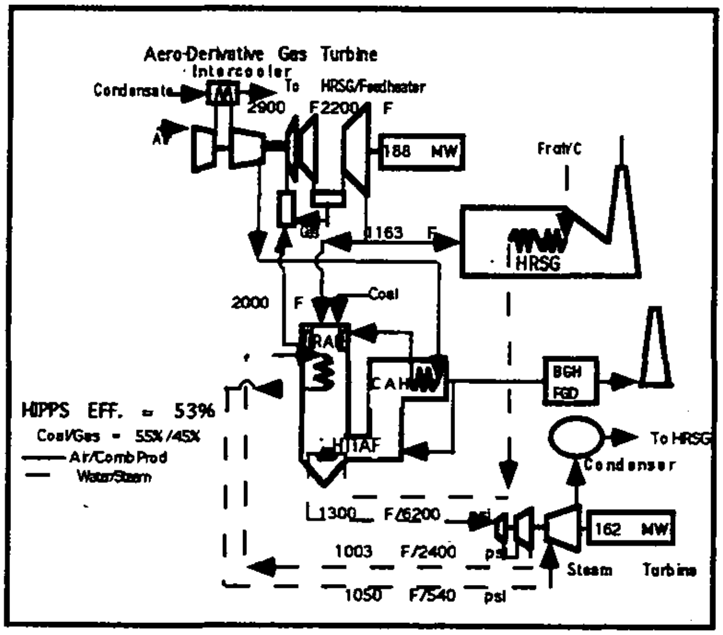

Fig. 5 - HIPPS/ICAD with reheat GT and advanced steam.

HIPPS/HAT

The ICAD engine was used as the basis of a Humid Air Turbine or HAT cycle in both the CAGT and Phase I ATS studies. A simplified schematic of a HAT cycle is shown in Fig. 6. In the HAT cycle, the compressor discharge air is sent to an aftercooler where heat is removed prior to going to a saturator. The saturator is similar to those used widely in the chemical process industry to to add vapor to various gas streams. The saturator could be of the packed column type or of the newer centrifugal type introduced by ICI. In the chemical process industry, the saturators operate at all load conditions, including emergency shutdowns, and show no significant performance degradation at part load. In the saturator, the cooled air is heated against water which has been heated in the intercooler and the aftercooler. The air, saturated with moisture at the outlet of the saturator, is then regenerated before entering the combustor. The amount of water in the air varies as a function of operating parameters, but can be as much as 25% by weight of the compressor discharge air. The limit is set by flame stability. This increase in mass flow results in significant power gains. For example, if the FT4000 ICAD were to have an output of 100 MW, its output in HAT configuration would be around 200 MW. The efficiency would be increased by 30% or more. While the HAT machine could use the same compressor as the ICAD machine, significant modifications to the combustor and to the turbine aerodynamics, cooling, and materials would be required.

The water usage for the HAT cycle is less than that for an equivalent combined cycle. Water recovery from the exhaust is possible, although it would require treatment before reuse in the cycle. Because of the high temperatures involved and the use of the humid air as a coolant in some turbine sections, water of boiler feedwater quality is needed.

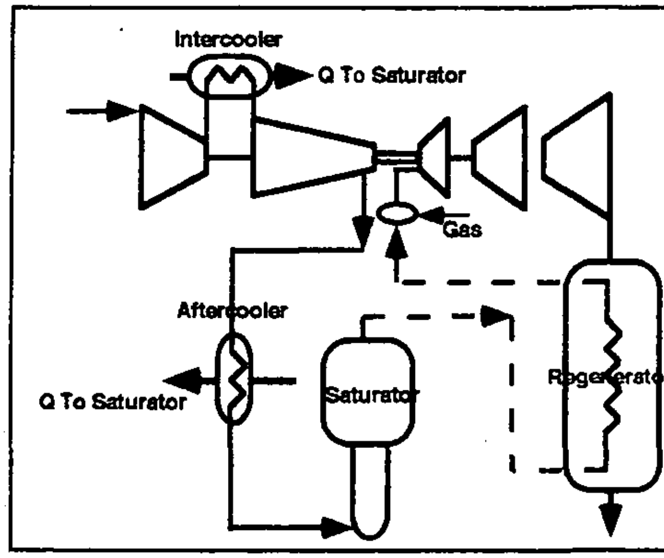

Fig. 6 - Simplified HAT cycle schematic

As in the case of the HIPPS/ICAD, the HIPPS/HAT is somewhat compromised by the DoE goal of having 65% of the fuel as coal. Unlike the HIPPS/ICAD combined cycle configurations, the HIPPS/HAT does not make as effective use of the lower grade heat from the HITAF. The heat remaining is only enough to supply approximately 25 MW of steam power. Since one of the more attractive cost benefits of the HAT cycle is the elimination of steam raising and steam turbomachinery (Robson, 1993) the addition of this very costly small turbine and associated heat recovery equipment can not be justified by the very small increase in cycle efficiency, approximately one percentage point.

One way of increasing the heat input to the gas turbine from coal is to increase the outlet temperature from the radiator in the HITAF. In the various configurations discussed to this point, the air preheat temperature from the radiator has been kept to 925 C (1700 F), a temperature which should allow components made from commercially available ODS materials to meet lifetimes typical of utility requirements (Seery et al, 1997). Similar materials have been demonstrated at outlet temperatures well above this level (Mabbutt, 1995) and should allow the outlet temperatures to be 1080 C (1975 F) or higher. Also, rather than use the GT exhaust as combustion air, a conventional air preheater for the HITAF combustion air would use additional HITAF exhaust heat. While these changes increase the fraction of cycle heat input from coal, the added moisture content in the combustion air means that the limitation of 35% gas fuel would allow only a 265 C temperature rise in the combustor (to 1345 C). Even with all these compromises, the first generation HIPPS/HAT (Fig. 7) would have an attractive performance; an output of nearly 200 MW at an efficiency of 49.3% (HHV), nearly one percentage point better than the first generation HIPPS/ICAD.

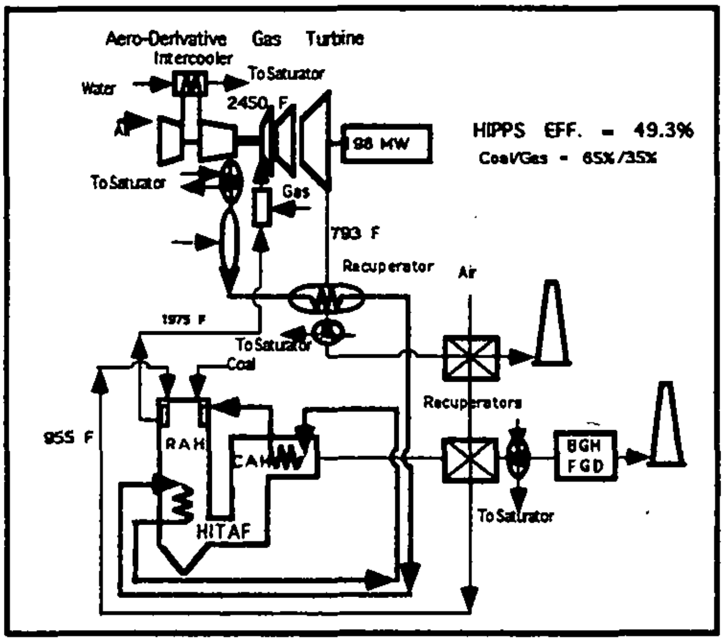

Fig. 7 First Generation HIPPS/HAT

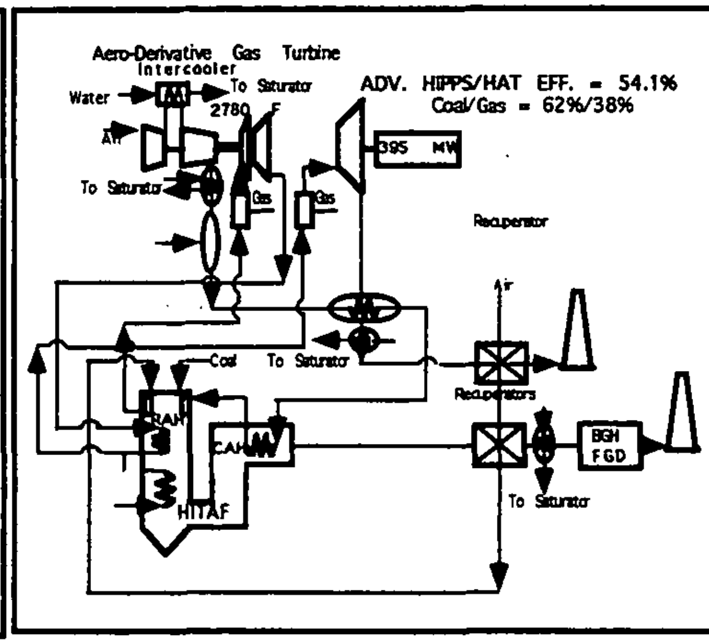

Fig. 8 Advanced HIPPS/HAT

The previous studies of the HAT cycle indicated that the two major problems that could limit higher turbine temperatures, cooling and NOx formation, would be mitigated by the use of humid air. Calculations indicated that NOx production might be held to less than 10 ppm at temperatures of 1595 C /2900 F and above with water fractions of 25% (Robson,1993). Advanced cooling methods could allow temperatures of over 1650 C/3000 F. Two configurations were investigated to identify higher performance HIPPS/HAT: 1) attaining a high temperature HAT while maximizing the fraction of heat input from coal; and 2) a very high temperature HAT with a minimum of 50% heat from coal.

To maximize the coal fraction while increasing the turbine temperature requires that more heat from coal be put into the cycle. Since the materials for the HITAF heat exchangers would still be limited to the 1080 C level, the additional heat must be put into reheating the turbine stream. This reheat HIPPS/HAT is shown in Fig. 8. After expanding through the high pressure and low pressure compressor drive turbines, the air is reheated first by coal in the HITAF to 1080 C and then a small amount of gas is used to bring it to 1205 C at the entrance to the power turbine. This results in a HIPPS/HAT with an output of 395 MW at an estimated efficiency of over 54% (HHV) and with 62% of the cycle heat from coal. By reducing the gas fuel to the combustor and lowering the inlet temperature, the coal fraction could have been raised to the 65% level as desired by DoE at a cost of approximately one to one and a half percentage points in efficiency. While having an attractive output and efficiency, the HIPPS/HAT reheat cycle is more complex than the cycle of Fig. 7.

By postulating a new goal for coal fraction, e.g, that at least 50% of the input heat is from coal, a higher temperature HIPPS/HAT can be defined. The new cycle, shown in Fig. 9, resembles the Fig. 7 configuration with a higher power output, approximately 325 MW and an efficiency of 54.3% (HHV).

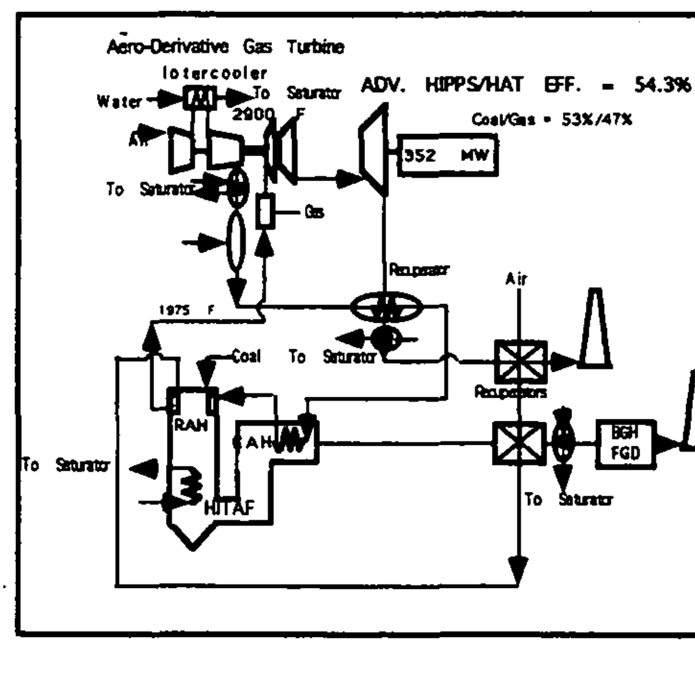

Fig. 9 - High Temperature HIPPS/HAT

Repowering

The electric utility industry in the United States is in a state of flux. A number of states have deregulated utilities and others are considering different means of restructuring the industry. While the final format for the industry remains undefined, it is generally conceded that the typical vertical integration of power generation, transmission, and distribution will no longer be the norm. Rather generators will sell to power brokers who may either transmit the power or further aggregate it for sale to another entity for end use. The major criterion for purchasing power will be low cost. This would seem to mean that existing plants with low marginal costs and new plants with low capital cost and high efficiency, i.e., gas fired combined cycles, would be favored. Thus, for the next several years, it appears that the industry may not be interested in coal-fired base load plants.

There are a number of reasons, however, that many of the aging coal-fired plants would make likely candidates for repowering. In its simplest terms, repowering is the integration of a gas turbine in an existing power plant to increase output and efficiency while reducing emissions. There are many types of repowering ranging from the relatively simple replacement of regenerative feedwater heaters by steam raised in an HRSG to configurations where the only remnant of the former plant is the fence around the boundary (Kudhu,1989). The HIPPS/ICAD could be an attractive method of repowering.

A series of parametric analyses were made to identify the potential performance and the conceptual configuration of steam plants repowered with a single FT4000 ICAD. In combined-cycle configuration, this engine was shown to be able to repower stations from 90 MW to over 200 MW in size with steam conditions ranging form 1250 psi/950 F non-reheat to 2400 psi/1050 F/1050F reheat. Efficiencies in the 42-47% range (HHV) were estimated (Fig. 10). A preliminary economic analysis indicated that the HIPPS repowering would have a cost of electricity (COE) that would be approximately 5% higher than a conventional gas-fired combined cycle at today's fuel costs (coal at $1.00/million Btu and gas at $2.00/million Btu), but would have a 15% to 20% advantage at fuel costs projected for 2010 (DoE, 1996). Having established the potential benefits of this approach, a site specific application was investigated.

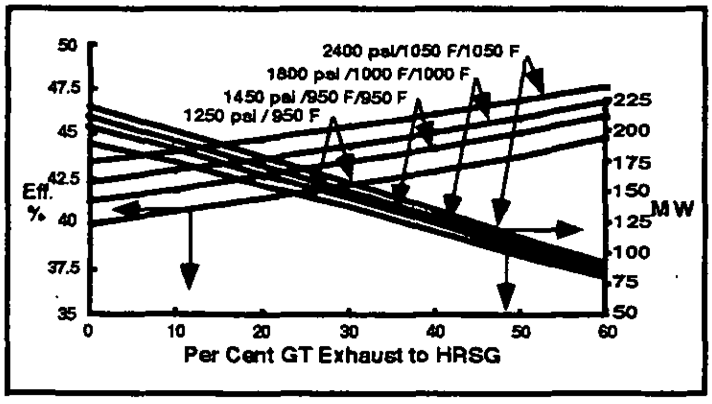

Fig. 10 - Results of Repowering Parametric Study

Information on a potential repowering site in upper New York state was supplied by DoE. The steam plant had an output of 122 MW at nominal steam conditions of 100 bar/535 C/535 C (1450 psi/1000 F/1000 F). Using these data on the original power plant, the UTRC Team identified a preliminary repowering configuration shown in Fig. 11. Because gas turbine exhaust replaces extraction steam for feedwater heating, the existing steam turbine would be faced with excessive back end steam flow. The entrance flow was reduced to meet the back end restrictions, cutting the turbine output from 122 MW to about 90 MW. To be consistent with previous HIPPS configurations, a RAH was used in the HITAF; future repowering designs will focus on use of a CAH only. With the addition of the ICAD gas turbine, the total plant output was approximately 202 MW at a gross efficiency estimated to be over 44% (HHV) some eight (8) points, or approximately 23% better than the original steam station.

The HIPPS aproach could also be used to repower gas-fired combined cycle plants, whether new or old. Currently, the price of gas for power generation is approximately twice the price of coal (DoE, 1996).

Emissions

Implicit in all of the HIPPS plants are emissions that are well below the current New Source Performance Standard for coal-fired plants. As was indicated in Table 1, HIPPS is to meet standards that are one-tenth of current NSPS. The HITAF has a low NOx burner as part of the design. Just prior to the CAH, a selective non catalytic reactor (SNCR) using urea injection further lowers the NOx. The HITAF exhaust has baghouses and flue gas desulphurization to meet the designated standards. If necessary, a selective catalytic reactor (SCR) could be installed.

The gas turbine exhaust is considered a separate source. The major concern is NOx as sulphur emission is quite low, both because the gas has very low sulphur, but also because only a fraction of the normal amount is burned. The duct burners for the HIPPS gas turbine use a very rapid mix design that produces very low NOx (<10 ppm) (Seery, 1995) in ICAD configuration and have even lower projections for the HAT configuration.

The growing concern with global warming from greenhouse gases makes the mitigation of CO_2 emissions of great importance. The higher efficiencies of the various HIPPS configurations results in significant reduction in these emissions as shown in Fig. 12 from Robson, et al, 1997. The CO_2 emissions in Fig. 12 are expressed in terms of grams of carbon equivalent. It should be noted that significant reductions can be realized without going all the way to very advanced technology. The repowering application of HIPPS/ICAD discussed above shows a 28% reduction in CO_2 emissions from the original steam plant.

HIPPS Economics

One of the goals of the HIPPS pogram is to produce power at a cost of electricity (COE) that is 10% less than that from current pulverized coal (PC) plants meeting NSPS. The Phase I commercial plant design previously mentioned was estimated to have a COE some 8% less than the PC plant (Seery, et al 1995). Subsequent effort in Phase II indicates that the commercial plant will more than meet this goal.

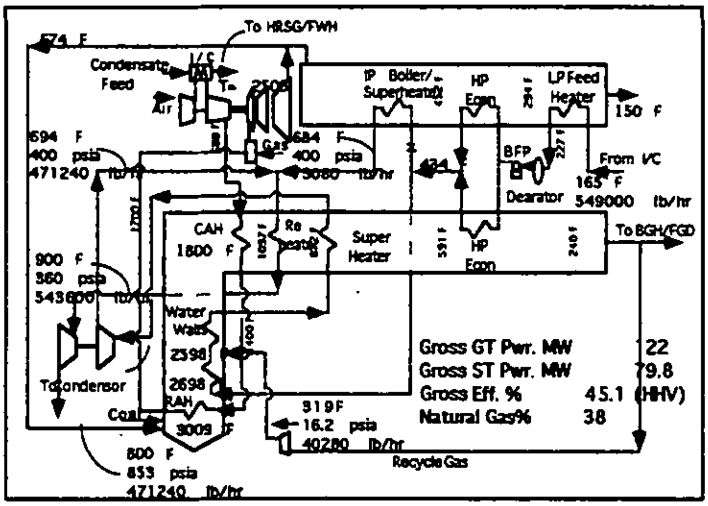

Fig. 11 Repowering Schematic

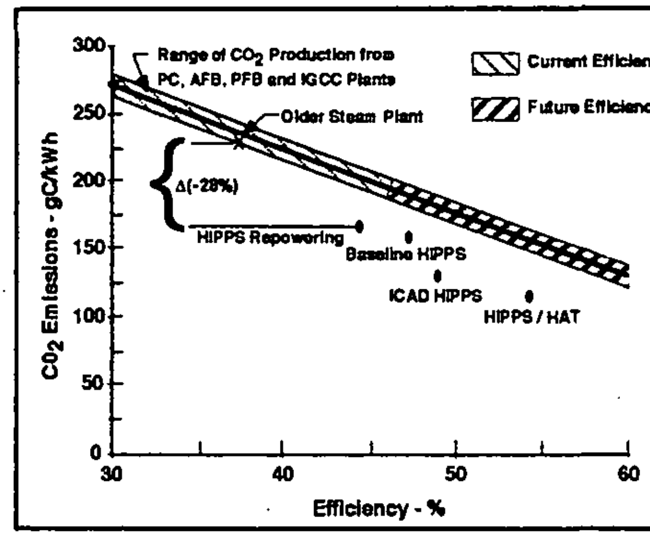

Fig. 12 CO2 Emissions

A cost analysis of repowering is of interest because it would indicate how the HIPPS competes against the system of choice, the gas-fired combined cycle. One of the major costs is that for fuel. Projections (DoE, 1995) indicate that the ratio of costs of pipeline gas to coal vary from approximately two currently, to three in 2012. In our cost analysis, these two values will be used for current and future cost ratios.

A nominal 200 MW steam plant operating at 1850 psi/950F/950 F was repowered using three alternatives: Aeroderivative HITAF; Aeroderivative Combined Cycle; and Heavy Frame Combined Cycle. The aeroderivative and heavy frame combined cycles both required supplemental firing to match the assumed steam conditions. In addition, a HIPPS/HAT producing the same power was analyzed. Costs were based on earlier Phase 1 effort and on unpublished reports on the Collaborative Advanced Gas Turbine program. Technology levels assumed for the aeroderivative and the frame engines are equivalent in terms of firing temperatures.

The cost of electricity was determined using the EPRI TAG® levelizing methodology. The results (Fig. 13) were then normalized with the Aeroderivative HITAF LCOE being unity at current fuel cost values. With a gas to coal cost ratio of two, the gas-fired combined cycle repowering systems offer a 4% to 5% lower LCOE, a difference within the cost uncertainty band. As the cost of gas increases relative to coal, the Aeroderivative HITAF becomes 10% to 20% more attractive. The HAT/HITAF would be approximately 5% lower in LCOE than the frame-type combined cycle at curent fuel costs and nearly 30% lower at the projected future costs.

Concluding Remarks

The HIPPS program has identified an advanced power system that uses coal to supply the majority of heat for gas turbine based power generation. The original HIPPS concept uses a frame machine to achieve efficiencies of over 47% (HHV) with emissions only one-tenth of NSPS. By applying a new generation of intercooled aeroderivative turbines that could be based on the latest high thrust commercial jet engines, future HIPPS could achieve efficiencies well over 50% (HHV) in combined cycle configuration and approaching 55% (HHV) in HAT cycle configuration thereby providing power at costs lower than gas-fired combined cycles. The majority of the key technologies necessary for these advances are currently being demonstrated or are under development in various government and privately funded programs. The commercialization of these technologies is now dependent on the market forces that will shape the new utility industry in the early 21st century.

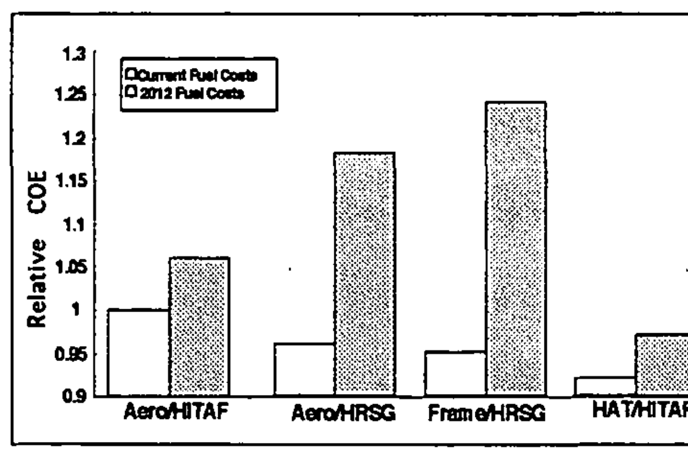

Fig. 13 Relative cost of electricity

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