High Performance Power Systems (HIPPS) – Opportunities and Options for the Coal-Fired Power Plant Market

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Abstract

The High Performance Power Systems (HIPPS) plant integrates a combustion gas turbine and heat recovery steam generator combined cycle arrangement with an advanced coal-fired furnace. A unique feature of the HIPPS plant is the partial heating of gas turbine compressor outlet air using energy released by firing coal in the high temperature advanced furnace (HITAF). The compressed air is additionally heated prior to entering the gas turbine expander section by burning natural gas. Thermal energy in the gas turbine exhaust and in the HITAF flue gas are used in a steam cycle to maximize electric power production. The HIPPS plant arrangement is thus a combination of existing technologies (gas turbine, heat recovery units, conventional steam cycle) and new technologies (the HITAF including its air heaters, and especially the heater located in the furnace's radiant section).

The DOE/FETC-sponsored HIPPS program has reported plant designs with estimated efficiencies approaching 60% in greenfield plants. The HIPPS plant concepts identified by the United Technologies Research Center team can be adapted to repowering of existing coal-fired plants. The HIPPS repowered plant has a significantly improved heat rate, reduced air emissions, increased generating capacity and the flexibility to match economic dispatch requirements. The HIPPS plants may be designed for either frame-type or aeroderivative gas turbines. The gas turbine typically receives two-thirds of its thermal input from air heaters in the HITAF and natural gas is burned to boost the turbine inlet air temperature from about 925 C (1,700 F) to levels suited to modern gas turbines. Recent encouraging test results with the HITAF air heat exchangers indicate that it is feasible to reach temperatures over 1,090 C (2,000 F). Thus, in some repowering configurations, up to 90% of the gas turbine inlet air heat energy could be from coal.

The potential repowering market, and the role of HIPPS technology in that market, was also identified as part of the HIPPS study effort. In the investigation of repowering, both the conventional HIPPS and advanced HIPPS with a variety of engine configurations and power cycles were analyzed. Depending on the gas turbine selected and the steam cycle parameters and configuration, increased power generation from the repowered plant ranged from 25 to 200 MWe or more, with efficiencies of 42% to 52%, based on fuel higher heating value. Because of the increased efficiencies of the advanced combustion technology, emissions of CO_2 and NO_x are significantly reduced.

Background

A key part of the U. S. Department of Energy's Combustion 2000 Program is the High Performance Power Systems (HIPPS). HIPPS is a multi-year, multi-phase program to develop technology for an advanced coal-fired furnace that provides preheated combustion air and steam for high performance combined cycles. The specific goals for the HIPPS program are shown in Table 1.

Table 1
DOE Goals for HIPPS

Green Field 300 MWe Commercial Plant Performance and Environmental Goals		
1. Power plant net thermal efficiency (higher heating value) of 47%.		
2. Minimum 65% coal energy input; path to 95% coal process.		
3. Cost of electricity at least 10% less than comparable NSPS power plant.		
4. Environmental performance requirements:	New Source Performance	HIPPS Phase II
• Sulfur Oxides (lb/MMBtu)	0.40*	0.06
• Nitrogen Oxides (lb/MMBtu)	0.50	0.06
• Particulate (lb/MMBtu)	0.03	0.003
• Solid Wastes	Benign	Benign
* Based on 90% reduction of the total sulfur in the fuel with the design coal (5.98 pounds of SO_2 per MMBtu; or 2.57 kg of SO_2 per million kJ) and a 65/35 ratio of coal and natural gas.		

Figure 1 is a simplified diagram of the HIPPS concept. The HIPPS differs from a conventional gas turbine combined cycle in that the compressor discharge air is sent to the coal-fired High Temperature Advanced Furnace (HITAF) shown in Figure 2, where the air is preheated first in a convective air heater (CAH) to about 700 C (1,300 F) and then in a radiant air heater (RAH) to approximately 925 C (1,700 F). The preheated air then goes to a special topping combustor where natural gas is burned to increase the air temperature to 1370 C (2,500 F). The topping combustors allow full operation of the gas turbine on the natural gas alone, increasing the plant's operating flexibility.

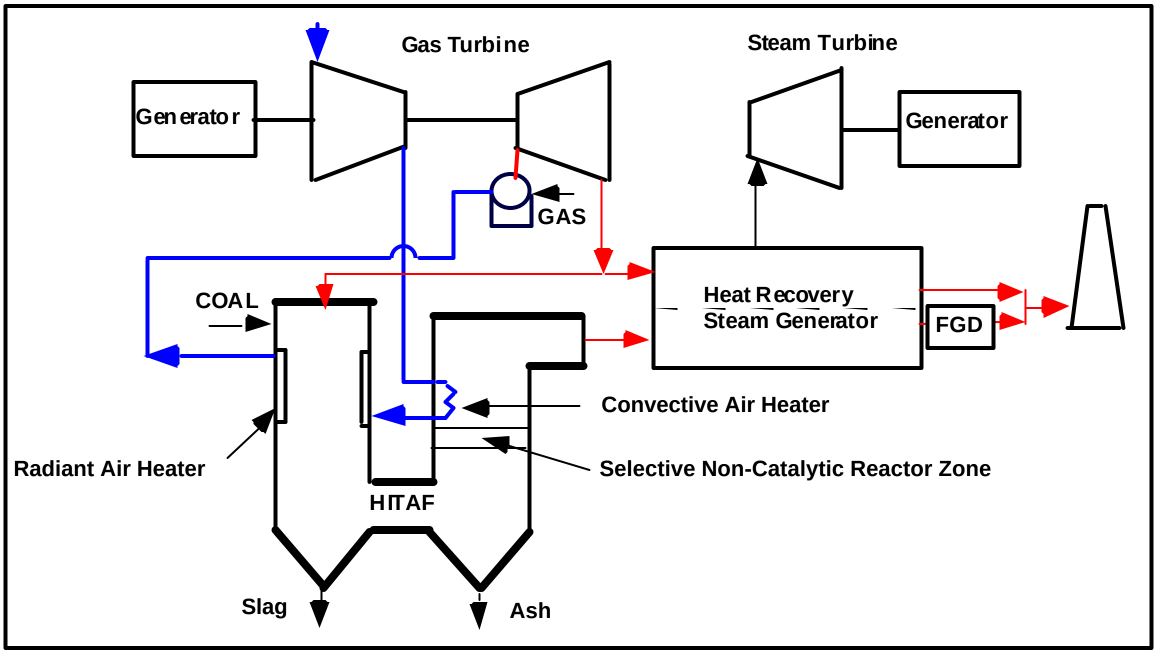


Figure 1
Simplified HIPPS Process Diagram

There are two options for the turbine exhaust: It can be split into preheated combustion air for the HITAF with the remainder going to an heat recovery steam generator (HRSG) as shown in Figure 1; or the entire flow can go to an HRSG. In the latter case, a conventional air preheater is used in the HITAF exhaust. The choice is based on customer preference. The exhaust from the HITAF is sent to a cleanup system consisting of particulate removal and desulfurization and, if needed, NO_x control. This system uses technologies being developed in other DOE programs. Much of the HIPPS/Combustion 2000 technology will be useful for the new DOE Vision 21 concept to increase efficiency, lower costs and minimize environmental issues for fossil power generation.

A commercial green field plant design[1] was defined based on 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). This commercial plant design was a minimum risk approach: With the exception of the radiant air heater portion of the HITAF, all the other components have been demonstrated or are commercially available. More advanced versions of the HIPPS have been investigated (e.g., Robson, 1995; and Robson, 1998). These advanced systems use frame type and intercooled aeroderivative (ICAD) gas turbines, some with advanced steam cycles, to obtain overall combined cycle system efficiencies approaching 53% (HHV). The ICAD also allows other advanced power cycles such as the Humid Air Turbine (HAT) cycle which can have efficiencies of over 55% (HHV).

[1] Robson, F.L., Ruby, J. and Seery, D.J. , High Performance Power System (HIPPS) Plant Design and Economics, Proceedings of the 20th Annual Coal Utilization and Fuel Use Conference, March, 1995.

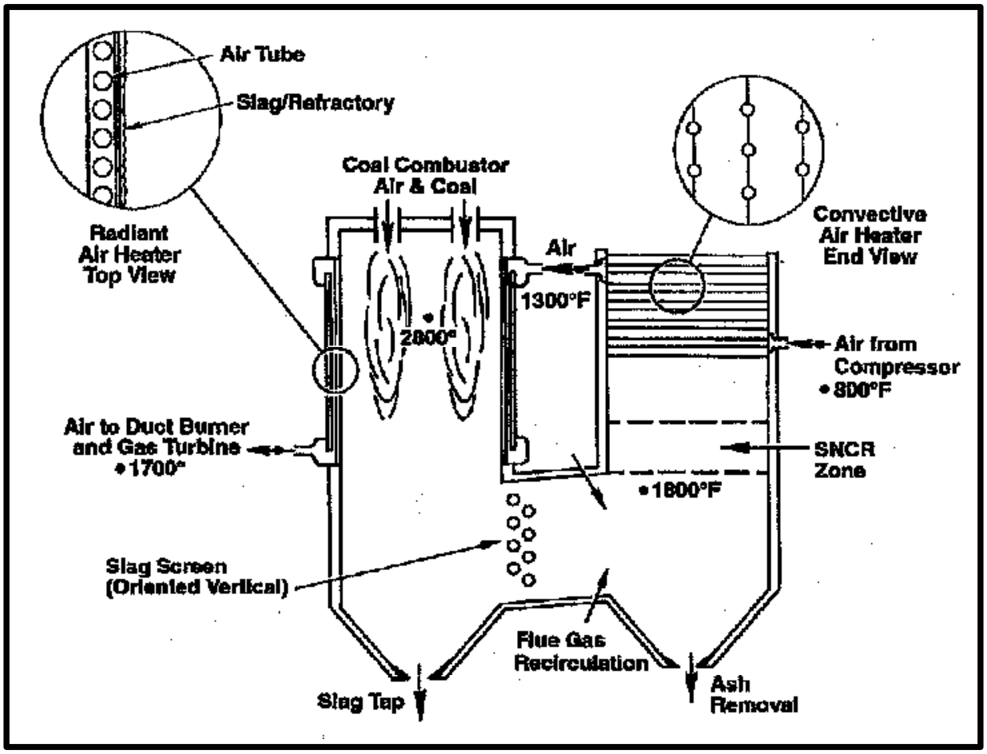


Figure 2
The High Temperature Advanced Furnace (HITAF)

These cycles are also applicable to repowering, a method of extending the life of older steam turbomachinery and, if warranted, steam generators. To complement the engineering and design work, a HIPPS market assessment task examined current electric power generation in the United States, and forecasts for future changes to the industry. The Energy Information Administration (EIA) of the U. S. Department of Energy was the source of most raw data[2]. The EIA data is collected from utilities, and usually does not reflect power generation by independent producers or others outside the regulated utility field. Seventeen states in the United States were selected as a focus of the study, and that selection was reduced to seven states where the effort can be concentrated to market the HIPPS technology. HIPPS is shown in the study as being competitive with other power generation technologies, including gas turbine combined cycle power plants.

Summary

In the next two decades, it is estimated by the EIA that over 400,000 MW of capacity addition will be needed to meet increased electrical demand and to replace aging units[3]. This includes approximately 73,000 MW of current coal-fired power scheduled to be retired during this period. Many of the plants currently scheduled for retirement could be

[2] EIA Inventory of Power Plants in the United States – As of January 1, 1997.
[3] Annual Energy Outlook 1998, with Projections to 2020; December, 1997. All values are from the EIA reference case.

successfully repowered using HIPPS at a lower cost than new generation capacity; with a significantly higher efficiency than the existing plant, and with the capability to meet strict environmental requirements. If desired at a specific site, it is also possible to double (or more) the generating capacity while repowering. The ability to use existing facilities and infrastructure and, in many cases, use locations near to load centers that already have many of the needed environmental permits makes repowering attractive.

The following points are major study issues, or result from estimates made in the study.

- Market size: 403,000 MW of capacity will be required by 2020 in the U. S. to replace older units and provide for growth. Only 49,000 MW of the new capacity is forecast as coal-fired, so for the HIPPS market to have the best opportunity to grow, HIPPS should compete with, and capture some of the forecast natural gas-fired capacity.

- Market size: The markets for HIPPS could range from 8,000 MW (20% of the planned coal-fired additions) to 80,000 MW (about 20% of the total capacity addition). This megawatt range equates to a cost range of from about $6 to $60 billion (in 1997 dollars) over the period from now to 2020.

- Market timing: Because of the planned retirements of existing units, more than half of the added capacity will occur in the 2010 to 2020 period. This allows time for HIPPS to demonstrate its performance and economic advantages.

- Repowering Market: The application of the HIPPS approach to repowering can cover a wide range of sizes and operating conditions. The economics are competitive with other advanced technology alternatives, and become even more attractive as the cost difference between coal and gas widens. Obviously, the selection of repowering technology among the various alternatives must be done on site specific considerations. The HIPPS concept gives a good deal of operating and fuel flexibility and allows the substitution of coal for a significant fraction of the gas in this application.

- Location: In the U. S., the states of Ohio, Indiana, Pennsylvania, Illinois, Missouri, Tennessee and Wisconsin were selected as having the “best” conditions for HIPPS to enter the power generation market. While not examined in detail, there may be major opportunities for HIPPS in the European and Asian markets where fuel prices and environmental limits drive power generation plants to the most efficient systems.

- Competitive Standing: From estimates made for the commercial plant design, HIPPS is clearly more economical than integrated gasification combined cycle and pulverized coal-fired technology on both a capital cost and cost of electricity basis. While having a higher capital cost, HIPPS is also competitive with gas turbine combined cycle plants based on the present value cost of electricity calculated in a range of power generation scenarios.

- Competitive Standing: The cost of electricity for HIPPS is competitive with the average prices paid for electricity in the 17 states examined by the study.

- Environment: The emissions from the all-coal HIPPS are significantly less than from other PC-fired plants. Another benefit is the reduction in CO_2 compared to typical coal-fired plants (Robson, 1997). Depending on overall plant efficiency and on the gas to coal ratio, a HIPPS plant can reduce CO_2 by 20% (all coal) to 40% (advanced aeroderivative HIPPS).

- Technology Development: Finally, current research with the HIPPS has identified and demonstrated many of the technologies required to achieve high efficiency power generation using coal, the number one energy resource in the world.

Market Statistics

A large amount of data was examined during the market assessment task. The items below distill some of the data to illustrate areas of special importance to the forecasts of a HIPPS market.

- The installed coal-fired capacity of the U. S. is 302,000 MW, or about 43 percent of the Nation's total capacity in 1997. About 30 percent of the coal-fired capacity began operation in, or prior to 1960.

- In general, the utility industry is a low growth area of our mature economy. Some of the low growth of electric power demand can be allocated to efficiency and other advances in generation and consumption technologies.

Table 2 shows EIA data for the United States utility industry as of 1997.

Table 2
Categories of U. S. Utility Industry Power Generation 1997

Energy Source	Megawatts Capacity	Percent of Total Capacity	Percent of Total Generation
Coal-Fired	302,523	42	57
Gas-Fired	142,566	20	9
Nuclear	100,756	14	20
Renewables	75,448	11	11
Petroleum	69,480	10	2
Pumped Storage Hydro	21,110	3	1

The Table 2 capacity data includes almost 4,800 MW of new (added in 1997) capacity, with this added generation split as 34 % coal; 36 % gas; 23 % nuclear and 7 % from other energy sources. Renewables (water, geothermal, solar, biomass and wind) total about 1 % of the capacity and less than 1 % of the generation when conventional hydroelectric is separated from the renewables category.

The Market in 17 States

Seventeen U. S. states were selected to focus our estimate of a market for HIPPS technology power plants. Data from the 17 states showed:

- Some 44,500 MW of coal-fired capacity started operation in 1960 or earlier.

- As indicated by fuel (coal and natural gas) use, growth in the 17 states has a wide variation. The variability may indicate areas of opportunity in an overall slow growth industry.

- Fuel prices in the 17 states follow a National trend for coal price to decline while natural gas price increases.

- Average electricity prices charged to the ultimate consumers in the 17 states ranged from 4 to 8 cents per kilowatt hour (kWh).

- The EIA forecasts that (Nationally) plants with an operating and maintenance cost greater than 4 cents per kWh will be retired in the next decade.

- There are some 5,000 MW of coal-fired capacity planned for addition during 1997 to 2006 in the U. S. 4,000 MW are planned in the 17 states. For natural gas-fired plants (gas turbines and gas turbine combined cycle) the figures are much higher; 32,000 MW for the U. S. and 22,000 MW for the 17 states.

- In addition to the planned additions in the 17 states, some 6,200 MW are planned for changes to their installed coal-fired capacity.

To illustrate the potential for repowering or replacement of aging plants, Table 3 lists age and other data for the states.

Table 3
Aging of Utility Coal-Fired Units for 17 States

	1997 EIA Data	Number of Units	Average Age years	Average Capacity MW	Oldest Unit	Total MW of Units 1960 and Earlier	Newest Unit
1	Texas	36	17	576	1971	0	1992
2	Ohio	99	35	240	1933	5,994	1991
3	Indiana	78	34	265	1925	3,804	1995
4	Pennsylvania	50	37	374	1948	4,019	1980
5	Kentucky	58	32	278	1950	2,427	1990
6	West Virginia	33	36	453	1943	2,859	1980
7	Illinois	41	34	257	1948	2,376	1982
8	Alabama	39	37	323	1908	3,768	1991
9	North Carolina	45	40	278	1940	3,085	1983
10	Georgia	38	35	381	1941	1,505	1989
11	Florida	31	25	380	1953	621	1996*
12	Michigan	48	35	257	1943	3,066	1985
13	Missouri	43	33	261	1948	1,091	1986
14	Tennessee	33	41	293	1951	6,105	1973
15	Wisconsin	48	40	141	1935	1,645	1985
16	Utah	9	23	451	1954	189	1987
17	New Mexico	10	26	428	1963	0	1984
	Total/Average	739	31	313	---	44,514	---

* One of the two units starting operation in 1996 is a integrated gasification combined cycle plant (Tampa Electric's Polk Plant)

Utility Planned Capacity Additions

Table 4 shows EIA data for the U. S. for additions of capacity over the years 1997 through 2006, and is presented to illustrate the overall planning by utilities for the near term future. As is clear, the largest planned additions are to be natural gas-fired units, some 32,000 out of the 42,000 MW total. Thus, in addition to the planned coal-fired additions, there is a large HIPPS market opportunity if some of the utilities planning to build gas-fired units could be convinced that HIPPS is a better business and economic choice.

Table 4
Planned Additions by Utilities

EIA Data for Utilities --1997 through 2006	Existing Number of Units	Nameplate Capacity MW	Number of Units to be Added	Nameplate Capacity MW
U.S. Total......................	10,422	756,484	370	42,079
Coal.......................	. 1,214	326,457	11	4,924
Petroleum.............	. 3,282	77,683	40	2,146
Gas........................	. 2,205	145,639	231	32,000
Water (Pumped Storage Hydroelectric)........	. 140	18,387	1	204
Water (Conventional Hydroelectric)........	. 3,340	72,566	64	767
Nuclear...................	. 110	108,976	--	--
Waste Heat..............	. 55	4,548	13	1,941
Other Renewable2/..........	. 76	2,228	10	97

Table 5 presents similar coal and natural gas data for the 17 states selected as a focus for the market task. It is clear that the plans for these states are also heavily weighted for natural gas.

Table 5
Planned Coal and Gas Additions by Utilities

EIA Data for Utilities --1997 through 2006		Coal		Natural Gas	
		Number of Units to be Added	Nameplate Capacity MW	Number of Units to be Added	Nameplate Capacity MW
1	Texas	6	4,151	21	2,413
2	Ohio	--	--	5	383
3	Indiana	--	--	23	3,406
4	Pennsylvania	--	--	5	602
5	Kentucky	--	--	8	1,007
6	West Virginia	--	--	--	--
7	Illinois	--	--	16	2,704
8	Alabama	--	--	5	554
9	North Carolina	--	--	12	3,041
10	Georgia	--	--	10	2,074
11	Florida	1	157	15	2,934
12	Michigan	--	--	--	--
13	Missouri	--	--	12	1,734
14	Tennessee	--	--	--	--
15	Wisconsin	1	60	13	1,190
16	Utah	--	--	--	--
17	New Mexico	1	233	1	103
	Totals	9	4,601	146	22,145

HIPPS Market Assessment

While the EIA data presented in the preceding sections are valuable and interesting, they do not by themselves say much about a market for HIPPS technology. The costs and performance of HIPPS, while still under development, are necessary additions to the database to assess the market. While repowering costs are too site specific to generalize, costs for the green field HIPPS have been estimated in relative detail and are used later as part of the assessment. The market assessment estimates answers to the following major issues.

- What are the markets for HIPPS plants?
- How large might the HIPPS market become?
- What is the timeframe for a HIPPS market?
- Where are the best HIPPS opportunities?
- What are the competitors to HIPPS in the power generation market? And, how does HIPPS compare to the competition?

Future Markets

The HIPPS plants will be mostly base load operations. While experience to date on cycling the refractories in the test furnace has been favorable, operability issues would dictate that the high temperature furnace run with few start and stop cycles. Since HIPPS will be one of the most efficient and low cost plants in a generation system, the economic dispatch would indicate a high utilization factor. There is also the advantage that, with the combination of a gas turbine and conventional steam system, HIPPS will be more flexible than a pulverized coal plant. For example, the HIPPS could have the gas turbine and part of the steam turbine generator system running solely on natural gas for peaking or mid-range duty.

The technology and the current power generation market indicate that HIPPS units will be moderate in size, say 100 to 300 MW. However, HIPPS is well suited for use as a modular component of a phased construction scheme, and could be used for much larger plants. If properly planned and executed, major economies of scale are possible in a large phased construction plant, e.g., a single flue gas desulfurization system for several HIPPS modules. Or the gas turbines could be installed and operated while the coal portion of the plant is being installed.

For the foreseeable future, HIPPS plants will be fueled with a combination of coal and natural gas. To attain high performance, an all coal HIPPS requires special materials development and engineering solutions to a number of problems before this version of the all coal case is feasible. Thus, the plant location should be sufficiently large for coal storage facilities and possibly ash disposal, and systems for supplying coal and gas should be reasonably near the plant site.

(Lower performance versions of all coal HIPPS, i.e., efficiencies of 35-40% HHV, could be built using the conventional HIPPS technology. Such versions could be attractive for use in areas of the world where current PC plant efficiencies are less than 30%.)

HIPPS is designed to operate as a good friend to the local community and the environment. The green field plant design criteria is 1/10 of the current emission limits for new coal plants, and systems to perform that level of control are included with the price and efficiency estimates for HIPPS. The high efficiency reduces greenhouse gas emissions compared to other coal based systems. Environmental cleanliness is one of the strong points for marketing HIPPS.

The HIPPS technology can be used in the U. S. and most other parts of the world. There are no special, high-tech equipment that need special operations and maintenance or training. HIPPS looks and operates very much like a conventional power plant. As long as the estimates for performance and economics hold true as the technology develops, a wide range of owners will want to use HIPPS. Utilities, independent producers, merchant plants and others will consider HIPPS for cases where coal is available and other conditions are favorable to adding electric power generation.

Future Market Size

One estimate of the potential market's limits can be made from EIA's estimates that from 1996 to 2020, some 403,000 MW or about 1,300 new plants (assuming an average capacity of 300 MW) will be needed in response to growth and replacement of retired plants. EIA also assumes that plants with operating and maintenance cost above 4 cents per kWh will be retired in the next decade. The retirements include 73,000 megawatts of fossil generation. This estimate for new plants is in addition to repowering and life extensions or other actions that power generators make take to reduce the need for new plants.

Almost 50% of the additions will be required in the 2010 to 2020 time because of planned nuclear plant retirements. The EIA forecast is that 85% of the new power will be from gas turbines and gas turbine combined cycle plants. Only 49,000 MW of new coal-fired capacity is forecast, and 58 percent of that generation will come online in the 2010 to 2020 time.

Thus for the new plants, the bottom of the HIPPS market is some portion of the 49,000 MW of coal-fired additions. Using 20 percent as an estimate of the portion of the total market available for HIPPS, that would mean that about 10,000 MW of capacity could be built, mostly in the 2010 to 2020 time period. If for example, 8,000 MW is built in that 10 year period, it would mean about 2 to 3 HIPPS plants would have to be installed each year (assuming an average capacity of 300 MW). Even at such a conservative estimate, HIPPS would seem to be a good business venture, and the timing is about right for industry to demonstrate and accept the technical and economic attributes of the technology. Given earlier HIPPS plant estimates of slightly less than $800 per kW, total installed cost, the 8,000 MW would equal costs for a buyer, or revenues to a seller of $6.4 billion (1998 dollars).

The HIPPS market could expend significantly if the technology is able to replace some of the new capacity planned for gas turbine combined cycle plants, which is about 354,000 MW. Even winning 5% or 10% of this capacity would more than double or triple the installation of new HIPPS plants, and based on cost of electricity estimates, HIPPS should be very competitive with gas turbine combined cycle for a number of scenarios.

In the nearer term, from the present to 2006, the potential market for replacements of existing coal plants is smaller. However, if HIPPS is technically ready and economically proved for this timeframe, there are also large planned gas-fired capacity additions that would be open to competition by a clean, economical HIPPS system.

Other technologies may also win portions of the demand for new capacity: Distributed power generation, using a number different generators – fuel cells, microturbines, diesel and gas engines, may have a significant role in future power generation. For example, Allied Signal has commitments for 3,000 microturbine generator units in 1999 and 10,000 units in 2000[4]. Each unit produces only 75 kW of power and their widespread use requires solutions of a number of issues, but they are part of the overall competition that makes any forecast of markets difficult and out-of-date relatively quickly if not periodically updated.

The repowering market, and HIPPS role in that area are more difficult to define. EIA data shows only about 2,000 MW of capacity planned for repowering or life extension for the 1996 to 2006 period, and very few coal units are included in the estimate. There may be more repowering and upgrading work planned by non-utility generators, but no data were found to define this. EIA did report that non-utility generators planned to add 4,000 MW of capacity in the years 1997 to 1999. For comparison, non-utility generating capacity in 1996 was about 73,000 MW.

Another target for repowering could be a portion of the 73,000 MW of fossil-steam (coal, oil and gas) capacity scheduled for retirement over the 1996 to 2020 period. However, each plant would require site specific analysis to evaluate that possibility.

In summary for the repowering market, because of the variability of site and unit specific conditions is difficult to estimate a future market. However, while it appears that the repowering market will be relatively small, it could be an important one for HIPPS to gain a foothold in the generation business. Even if just one of the plants planned for repowering or life extension in the next ten years would use the HIPPS technology, that would benefit the future market. Over the longer term, to 2020, more repowering opportunities for HIPPS are likely. However, it is noted that adding repowered capacity is likely to replace or substitute for new plant capacity described in earlier paragraphs.

[4] T&D Electric World, December 1998 Volume 212; A publication of the McGraw-Hill Companies.

One conclusion that can be fairly draw is that the combined new plant and repowering market for HIPPS, which as reasoned above is to be conservatively on the order of $6 to 7 billion in the 2010 to 2020 period, should be large enough to attract business interest. Other market factors are examined next, but purely from the size of a potential market, HIPPS seems worth pursuing.

Future Market Timing

As reported earlier, the EIA forecasts a major need for additional capacity in the 2010 to 2020 period, largely because of planned nuclear plant retirements. HIPPS technology should be available to meet part of the requirement.

As with all developing technologies, schedules depend on many internal and external factors, but the sequence and milestones below reasonably estimate HIPPS progress. The time frame and milestone intervals may seem long, but at least for U. S. utilities, the cycle is typically 5 to 10 years from planning a new/repowered plant to approval and start of engineering and construction.

- Engineer, install and test a near commercial scale HIPPS system by the end of year 2003. That allows five years from now – almost 1999, until the first milestone.
- Install the first commercial unit using tax incentives or other subsidies by 2006.
- Install first unsubsidized system by 2010.
- Beyond this, the rest of the success for HIPPS will depend on its performance and changing conditions in the industry: gas turbine and other technological advances; fuel prices; electric power supply and demand; and numerous others.

If HIPPS can develop and become commercial by approximately 2010, the technology would be sufficiently tested in commercial conditions to be deployed on as large a scale as made feasible by the demand for electric power and competing generation systems.

Future Market Locations

By evaluating the various factors for plants in the 17 selected states, the "best" locations were estimated to be: Ohio, Missouri, Tennessee, Indiana, Pennsylvania, Illinois, and Wisconsin.

While our market study does not include assessment of foreign opportunities, the first markets for HIPPS may be outside the U. S. In parts of Asia especially, natural gas and liquefied natural gas are expensive and domestic distribution systems are limited, but coal mining and coal transportation are more developed mature industries. Also, most of the developing countries with coal, gas and oil resources would prefer to sell the gas and oil for dollars, which can be used for imports and investment funding. The demand for energy and environmental improvements is high in Asia and Eastern Europe, both of which could benefit from coal-fired HIPPS, even the lower efficiency, all coal versions.

Competitors in the Market

The main competition for HIPPS are plants using gas turbine combined cycle power plant technology, and the future GTCC systems which will be cleaner, more efficient and may cost the same or less than today's GTCC plants. In some special markets, for example where the owner has determined that coal will be used as the primary fuel, HIPPS will be competing against pulverized coal-fired plants, integrated gasification combined cycle and possibly, systems using atmospheric and pressurized fluid bed combustion technologies.

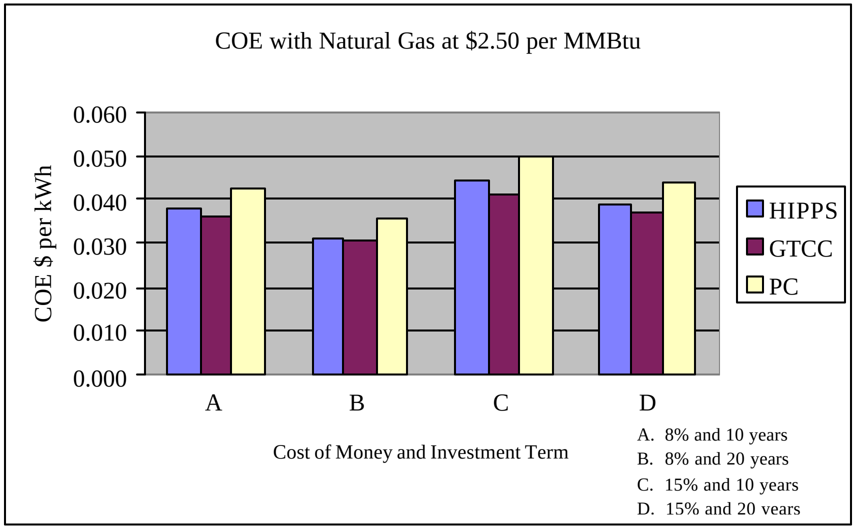
Table 6 presents a summary of the investment cost estimated for the green field HIPPS plant. The HIPPS plant is clearly less expensive than the pulverized coal-fire plant. Published and in-house data was used to estimate the gas turbine combined cycle plant, and $800 per kW was used for a Total Capital Cost, consistent in definition with the other technologies. The three plants are also consistent in capacity and environmental requirements. While the GTCC plant has the lowest capital cost, its fuel is more expensive.

Earlier work did not include an estimate for coal gasification combined cycle, but even the more optimistic estimates for IGCC are some $200 per kW more that the HIPPS and PC plants. The IGCC efficiency is lower than for HIPPS, and to show reasonable economics, the IGCC plant may have to be significantly larger capacity, thus increasing the magnitude of the investment required.

Table 6
Cost Estimates for Green Field HIPPS Plant Comparison

Cost Items	HIPPS Plant		Pulverized Coal Plant		Gas Turbine Combined Cycle Plant	
	Thousands of 1997 Dollars	$ per kWh	Thousands of 1997 Dollars	$ per kWh	Thousands of 1997 Dollars	$ per kWh
TOTAL CONSTRUCTION COST	238,800	796	258,300	861		
Project Contingency 15 % of TCC	35,820	119	38,745	129		
Total Plant Cost	274,620	915	297,045	990		
Allowance For Funds During Construction 8%	21,970	73	23,764	79		
Total Plant Investment	296,590	989	320,809	1,069		
Owner Costs 5% 0f TPI	14,829	49	16,040	53		
Total Capital Cost	311,419	1,038	336,849	1,123	240,000	800

To account for the differences in fuels and performance, cost of electricity (COE) was calculated for several scenarios. Figure 3 presents the results comparing HIPPS, PC and GTCC. The figure shows the results of calculating COE present values for three prices of natural gas, and four sets of cost of money and investment time period criteria (Indicated by A, B, C and D on the graphs.).



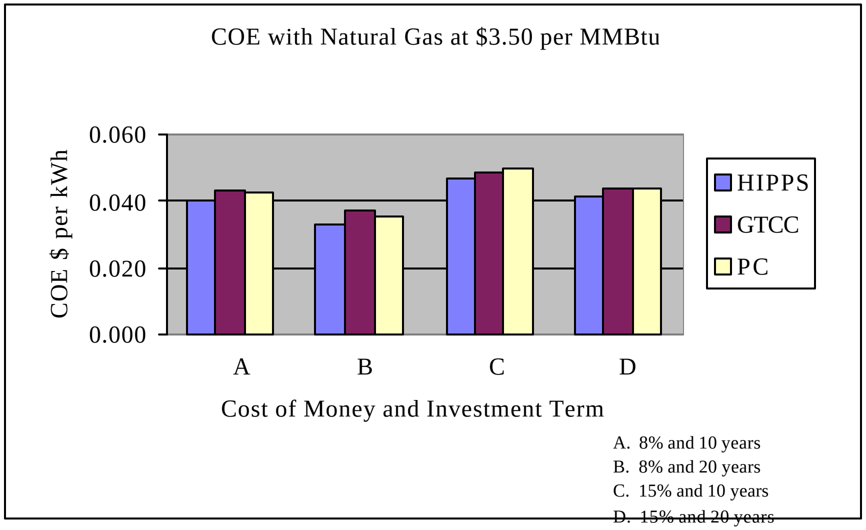
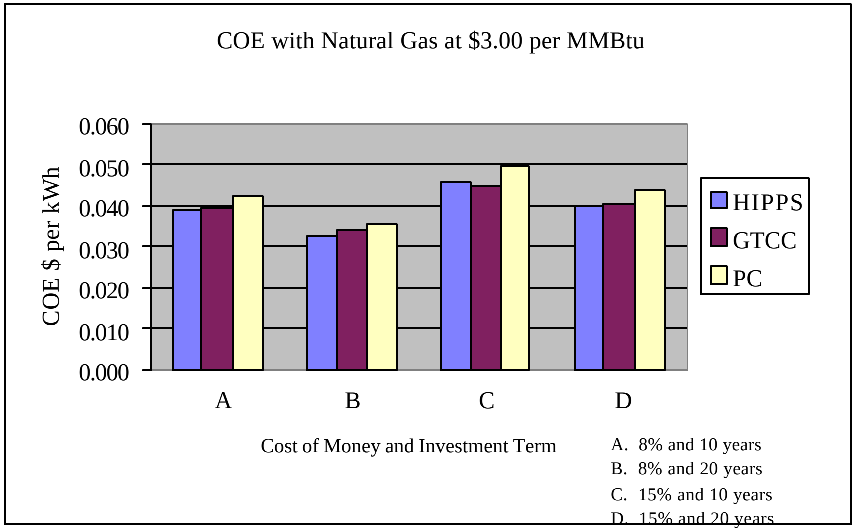


Figure 3
Present Value Costs of Electricity for Different Scenarios



In Figure 3, the relatively small difference between costs of electricity for HIPPS and GTCC power is clear. While the pulverized coal-fired COE is almost always the highest, the COE for HIPPS and GTCC plants sometimes give the advantage to one, and in other scenarios to the other technology. High natural gas prices favor HIPPS (and even PC plants at the higher gas costs); low costs of money and longer investment horizons also favor HIPPS as they reduce the impact of its higher capital costs. Conversely, the higher costs of money and shorter investment periods favor the less capital intense GTCC.

The EIA reported average electricity prices for the 17 states as between $.04 and .08 per kWh. The HIPPS and GTCC plants are competitive with existing power generators: Even with reasonable additions to the COEs for HIPPS and GTCC for transmission and distribution and profits, the estimated COEs will be less than a number of existing plants' prices for electricity.

Coal was priced at $1.14 per million Btus for the HIPPS conceptual design and estimates. For reference, the average price of natural gas delivered to U. S. utilities in 1997 was $2.76 per million Btus[5].

While the calculations show that HIPPS and GTCC technologies are close competitors, it must be fairly noted that HIPPS is still a developing system, while GTCC plants are in many commercial operations. Both HIPPS and GTCC technologies will continue to advance --increasing efficiencies, reducing emissions and lowering costs of electricity. The selection of HIPPS, once it is commercially available, or GTCC will likely be decided on site, fuel, and plant owner's requirement specifics.

Repowering Cycle Studies

Previous studies of the HIPPS determined that an advanced aeroderivative gas turbine system could have a performance advantage over one based on a heavy frame machine. The gas turbine in those studies was based on a multi-shaft aeroderivative design which could be derived from the 100,000 lb. thrust class aircraft engines such as the General Electric 90, the Pratt & Whitney 4000, and the Rolls Royce Trent. There has been considerable interest in industrialized versions of these engines using intercoolers; this configuration, given the acronym ICAD – InterCooled AeroDerivative, would offer high efficiency and high power density[6]. The ICAD also lends itself to greater flexibility in cycle configuration.

In a concept definition analysis, a single FT4000 I/C (intercooled) was used as the gas turbine. The investigation identified the ranges of steam plant sizes, steam conditions, and repowered plant configurations that could be accommodated with a single engine. Other sizes would then be scaled accordingly. Since repowering presents a near term

[5] Electric Power Annual 1997 Volume 1 by the EIA.
[6] Davidson, Barry and George Hay, Advanced Aeroderivatives and the CAGT Programme, Innovative Repowering Strategies with Advanced Gas Turbines, Washington, D.C., June 4-5, 1996

opportunity, it was decided in this analysis to investigate a first generation HIPPS, one that eliminates the radiant air heater (RAH) and uses only a convective air heater (CAH) in the HITAF. The RAH requires the most development and represents a higher technology risk than other HITAF components. The CAH, which can be constructed of materials available today, will still allow air to be heated to relatively high temperatures, 700 C – 800 C.

A single engine can accommodate a wide range of steam plants by varying the amount of exhaust gas sent to the HRSG (Figure 4). The steam systems range from a moderately high- performance 165 bar/565 C/565 C (2,400 psi/1,050 F/1,050 F) reheat cycle to a 86 bar/510 C (1,250 psi/950 F) non-reheat cycle. The corresponding efficiencies for each cycle are given in Figure 4 also 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 essentially constant at approximately 110 MW for the cases presented. The CAH outlet temperature was varied from approximately 700 C to 800 C (1,300 F to 1,500 F) with no significant impact on efficiency.

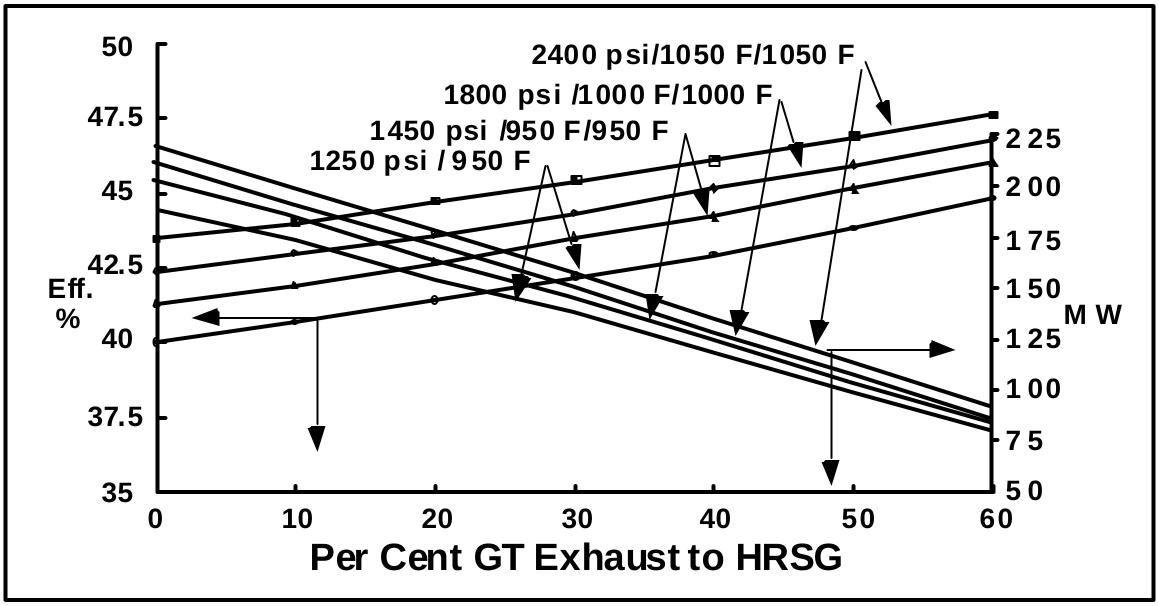


Figure 4
Repowering Characteristics

The configuration for the HIPPS repowered plant would be similar to the schematic in Figure 1, except that the radiant air heater would not be used. The boiler in the repowered plant is assumed to be of conventional design in regard to steam generation, superheat and reheat provisions. The GT exhaust is used as combustion air, allowing both the furnace exhaust and remaining GT exhaust to be used for feedwater heating, eliminating the need for many or all extraction heaters. The CAH, which heats the GT combustion air, is located in the furnace exhaust at the point where the temperature is 980 C (1,800 F). This temperature is ideal for non-catalytic NOx reduction and, for coals such as Illinois No. 6, avoids ash densification permitting reasonable operating times between soot blowing. To match combustion air requirements of different sizes of steam equipment, a portion of the gas turbine exhaust bypasses the furnace and is sent to a HRSG where it heats feedwater for the steam cycle.

The preliminary analysis of repowering with aeroderivative engines has shown as much as 10 or 12 points (around 30-35%) can be added to the efficiencies of older steam stations. As mentioned above, repowering configurations do not use the radiant heat exchangers simplifying the HITAF, which 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.

In actual operation, compromises between operational considerations and performance will have to be made. These compromises will be predicated on type of repowering application, e.g., baseload, mid-range, etc. and also on the experience of the specific utility or other user. The real-life configuration and operation, and thus, the economics, will be very site (application) specific.

All Coal Repowering

Until recently, the designs of the HIPPS have limited the temperature of the air from the HITAF to a range of 925 C to 1,000 C (~1700 F to 1825 F). Tests of a radiator segment (Figure 5) in a coal-fired furnace at the Energy and Environmental Research Center at the University of North Dakota have demonstrated the soundness of the UTRC design. Air has been routinely heated to temperatures of over 925 C (1,700 F). While not all the questions of refractory durability and structural design have been answered, over several thousand hours of tests have demonstrated the technologies needed in a coal-fired, high temperature air heater and have pointed the way toward solving the remaining problem areas.

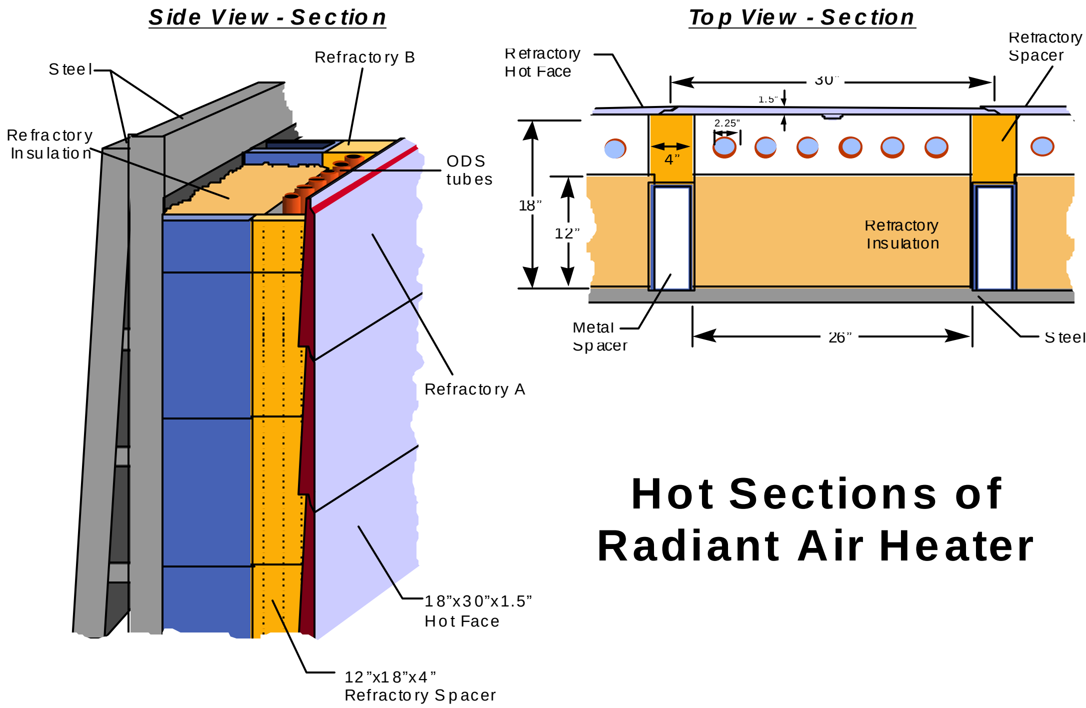


Figure 5
Schematic of Radiant Air Heater

In addition to the MA754 used in the current design, materials experts at UTRC have identified several advanced alloys currently capable of commercialization (e.g., PM 2000 and MA 6000) which would be suitable for radiator tubes with gas outlet temperatures of 1,150 C (2,100 F). Other tests using these ODS materials for high temperature heaters have been carried out. At the Research Center for British Gas, a radiator capable of 1,150 C gas outlet temperatures was used to supply heated air to a closed-cycle gas turbine[7]. The UTRC Team reviewed the test furnace operations at UNDEERC and decided to increase air outlet temperatures. In Nov. 1998, air outlet temperatures of over 1,090 C (2,000 F) were attained with Illinois No. 6 fuel and reported[8]. The ability to reach this air outlet temperature with coal alone means that an all-coal HIPPS becomes an attractive possibility. A HIPPS of this type would be usable in those areas having little indigenous gas or no access to economic premium fuel supplies. It also means that older coal-fired power plants could be repowered with a minimum requirement for premium fuel.

An investigation of an all coal HIPPS repowering was performed. The basis of the repowered plant was a steam system operating at 100 bar/535 C/535 C (1,450 psi/1,000 F/1,000 F). The outlet temperature of the RAH was set at 1,150 C (2,100 F), a viable

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[7] Mabbutt, Q. J., Cost 501 Work Package IV Final Report - O.D.S Closed Cycle Heat Exchanger Programme, Bgplc Research & Technology, July, 1995

[8] Science Daily, Hot New technology Offers Potential to Cool Global Warming, Dec. 16, 1998.

goal when using the newer ODS materials. This temperature level also allows the use of a number of existing gas turbines including currently offered aeroderivatives such as the GE LM2500 and the P&W FT8. While these machines normally operate at somewhat higher temperatures, operation at 1,150 C would not greatly compromise performance.

The configuration of the all coal HIPPS for repowering uses four 25 MW engines. This configuration could have great operating flexibility. Even in the all coal case, the gas turbines would require either natural gas or liquid fuel for start up. If these fuels were available at reasonable cost, the plant could operate in a number of modes. If desired, the gas turbine could be equipped with conventional burners to allow rapid start up on premium fuel, producing revenue during the shift to coal fuel. While the high efficiency would dictate base load operation, the flexibility would also allow mid-range and load-following operation. In the configuration investigated, the HIPPS could supply peaking power at levels from 25 MW to 100 MW, or it could operate with coal alone (after startup) to provide mid-range or baseload power at efficiencies will over 42% (HHV).

An existing power plant was used for a repowering analysis. It has a nominal 122 MW steam turbine operating at 100 bar/540 C/540 C (1,450 psi/1,000 F/1,000 F). The performance estimates for several configurations using four FT8-type gas turbines are presented in Table 3. Even at temperatures obtainable with present-day materials, the all coal repowering has an efficiency of over 42%, a gain of nearly 15% over the original steam plant.   At 1,150 C (2,100 F), the repowered plant is more than 7 percentage points, about 20%, more efficient.

Another aspect of fuel flexibility is the HIPPS can be designed to burn low-grade fuels and renewable resources such as biomass, either as the sole fuel or in a mixture with coal. This ability could make the approach attractive for emerging economies.

Table 3
Performance of FT8 Plants

	Base GT FT8	HIPPS 1,800 F	HIPPS 2,100 F
Number of GT engines	1	4	4
Type of fuel	Natural Gas	Coal	Coal
System Performance			
Total net power, MW	26	191.2	202.8
Gross Gas Turbine power, MW	25.5	64.3	82.8
Gross Steam Turbine power, MW	0	136	128.9
GT Cycle Efficiency, net (LHV gas)	38.7%	NA	NA
Cycle Efficiency, gross (HHV)	NA	42.30%	44.70%
Gas Turbine Performance			
GT HPT temp, F	------	1,800	2,100
GT LPT temp, F	------	1,308	1,515
GT exhaust temp, F	857	667	775
GT stack temp, F	857	180	180
Gas /Coal Ratio, %	NA	0	0
HITAF Combustor			
Coal flow rate, lbs/sec	NA	35.52	35.52
Radiant sect., GT Outlet NA temp, F	NA	1,800	2,100
HITAF stack temp, F	NA	300	300
Repowered Steam System			
Throttle flow, lbs/sec	NA	209.9	199.1
Pressure, psia	NA	1,477	1,477
Temperature, F	NA	956	956
Reheat turbine flow, lbs/sec	NA	209.9	199.1
Pressure, psia	NA	454	454
Temperature, F	NA	1008	1008

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Additional Literature

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2. Robson, F.L. and Seery, D.J., Advanced Aeroderivative Gas Turbines in Coal-Based High Performance Power Systems (HIPPS), ASME International Gas Turbine Conference, Stockholm, Sweden, 1998.

3. Seery, D.J., et al., Coal-Fired High Performance Power Generating System, Final Report to the U.S. Department of Energy, United Technologies Research Center, August 31, 1995.