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**Advanced Turbine Systems Program
Conceptual Design and Product Development
Task 4.0**

Topical Report

June 1994

Work Performed Under Contract No.: DE-AC21-93MC30247

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
Westinghouse Electric Corporation
Orlando, Florida

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ABSTRACT

This Topical Report presents the results of Task 4 of the Westinghouse ATS Program. The purpose of Task 4 is to determine the technical development needs for the conversion of the gas-fired ATS (GFATS) to a coal-fired ATS (CFATS). Two closely related, advanced, coal-based power plant technologies have been selected for consideration as the CFATS -- air-blown, coal gasification with hot gas cleaning incorporated into an Integrated Gasification Combined Cycle (IGCC), and the Second-Generation Pressurized Fluidized Bed Combustion (PFBC) combined cycle. These are described and their estimated performance and emissions in the CFATS are reported. A development program for the CFATS is described that focuses on the major commercialization issues. These issues are in the areas of combustion, flow distribution, structural analysis, and materials selection.

Section 1

INTRODUCTION

Currently, development and demonstration programs are under way that are applying advanced, coal-fueled technologies for clean, effective power generation using the current generation of combustion turbines. Integrated Gasification Combined Cycles (IGCC), Pressurized Fluidized Bed Combustion (PFBC), and Second-Generation PFBC are examples of advanced, coal-fueled technologies that will be demonstrated in the next 5 to 10 years.

A natural gas-fired Advanced Turbine System (GFATS) reference system has been selected and described by Westinghouse in the Topical Report that describes the results of Task 3, Selection of GFATS. The GFATS meets the established Advanced Turbine Systems (ATS) program goals for power plant thermal performance and emissions. It is prudent to consider the conversion of this GFATS to a coal-fueled Advanced Turbine System (CFATS) as a strategic development for the future when clean fuels, such as natural gas, are in limited supply. This will ensure the clean, efficient use of coal-based fuels in the future, and represents an evolution of the currently developing, coal-fueled power generation technologies.

Section 2

SUMMARY AND CONCLUSIONS

Two coal-fueled power plant technologies were selected to represent the CFATS -- air-blown, fluidized bed gasification using hot gas cleaning, and Second-Generation PFBC. Both of these are currently being demonstrated in major Clean Coal Technology Programs, and both have high performance and improved emissions control potential in the CFATS.

Both of these CFATS cases pose similar requirements on the combustion turbine, but they also differ in some respects. The IGCC case can utilize rich-lean, low-Btu fuel gas combustion baskets located within the combustion turbine cylinder. The Second-Generation PFBC case may require the use of external combustors due to the large size of the combustor chambers. The Multi-Annular Swirl Burner (MASB) will be used for this application, and an air-cooled inlet scroll will introduce the combustion gas into the turbine.

Major development areas directly relating to the conversion to the CFATS, in addition to those areas already identified in current coal-fueled technology development programs, are:

- Low-Btu, low-emission, fuel gas combustor design,
- Combustor outlet manifolding and turbine inlet scroll design,
- Turbine deposition and materials selection.

A 51-month development program for the CFATS has been devised. The program consists of segments to test a low-pressure, subscale CFATS rig; and a full-pressure, full-scale rig, both with integrated manifolding and scroll sections.

Section 3

SELECTION OF COAL-FIRED PLANT REFERENCE SYSTEM

A number of advanced, coal-fired power generation technologies have been under development that could be applied to the GFATS. These include a broad range of coal gasification technologies (fixed bed, fluid bed, and entrained bed), Second-Generation PFBC, and Direct Coal-Fired Turbines (DCFTs). Two advanced, coal-fueled technologies have been selected for consideration as CFATS: Air-blown IGCC with hot gas cleaning, based on the KRW fluidized bed gasifier; and Second-Generation Pressurized Fluidized Bed Combustion (PFBC). The rationale for these selections is summarized in this section.

The selection of a coal-fired reference system for the conversion of the GFATS to a CFATS has been made based on performance potential (power conversion and emissions), cost potential, and state of development. Table 3-1 summarizes estimated thermal conversion performance, cost potential, and indicates the status of development of several advanced, coal-fueled technologies that could achieve the desired turbine inlet conditions. These are compared to natural gas-fired turbine cycles, as well as to conventional coal-fired power plants -- Atmospheric-pressure Fluidized Bed Combustion (AFBC) and pulverized-coal combustion boilers with flue gas desulfurization (PC/FGD). The estimates represent performance using currently available combustion turbine technology and standard combined-cycle design conditions. The values in the table are representative, and should be applied for general comparison purposes only. Such results are sensitive to coal type, site location and conditions, and process design specifics. The air-blown IGCC technologies with hot gas cleaning, and Second-Generation PFBC appear to have the greatest thermal performance and cost potential. Their respective status of development is categorized as "early demonstration," which is suitable for the ATS program.

Table 3-2 summarizes the environmental emissions performance of these same technologies. Shown are emissions of NO_x , SO_2 , CO_2 , particulate, and solid waste that the technology can economically achieve, and they are presented on the basis of the plant net generating output (lb/hr per MWe), rather than on the basis of fuel input (lb/MBtu). A typical bituminous coal composition was applied to make the estimates (ash content 10 wt%, sulfur content 3 wt%, LHV 12,940 Btu/lb). All of the advanced technologies are

Table 3-1 - Performance of Alternative Power Generation Technologies

	Heat Rate Btu/kWh (LHV)	Cycle Eff. % (LHV)	Capital \$/kW	COE mills/kWh	Status of Development
<u>Advanced Technologies</u>					
IGCC (O ₂ -blown) ^a	8690	39.4	1500	76.9	Near commercial Early demonstration Developmental
IGCC (Air-blown) ^b	7380	46.7	1350	71.7	
Direct-Fired ^c	7170	47.7	1300	68.5	
2nd-Gen. PFBC	7580	44.6	1250	68.0	
<u>Conventional Technologies</u>					
AFBC	9600	35.2	1550	83.5	
PC/FGD	9600	35.2	1530	82.5	
Gas Simple-Cycle	8300	41.0	390	72.6	
Gas Combined-Cycle	6600	52.2	550	68.0	

a: Entrained, oxygen-blown gasifier with conventional coal gas cleaning

b: Fluidized bed, air-blown gasifier with hot gas cleaning

c: Slagging, air-blown gasifier with hot gas cleaning

Table 3-2 - Emissions of Alternative Power Generation Technologies

	NO _x	Emission (lb/hr/MW _e)		Particulate	Solid Waste
		SO ₂	CO ₂		
<u>Advanced Technologies</u>					
IGCC (O ₂ -blown) ^a	1.7	0.40	1774	6.7	79.0
IGCC (Air-blown) ^b	1.5	0.68	1506	5.7	226.9
Direct-Fired ^c	1.4	0.67	1464	5.6	166.0
2nd-Gen. PFBC ^d	1.5	1.76	1547	5.9	215.3
<u>Conventional Technologies</u>					
AFBC ^e	2.8	4.45	1959	22.2	256.3
PC/FGD ^f	5.7	4.45	1959	22.2	244.6
Gas Simple-Cycles ^g	0.8	---	1061	---	---
Gas Combined-Cycle ^g	0.7	---	843	---	---

a: NO_x 0.2 lb/MBtu, sulfur removal 99%, particulate 0.01 lb/MBtu

b: NO_x 0.2 lb/MBtu, sulfur removal 98%, Ca/S 2.0, particulate 0.01 lb/MBtu

c: NO_x 0.2 lb/MBtu, sulfur removal 98%, Ca/S 1.8, particulate 0.01 lb/MBtu

d: NO_x 0.2 lb/MBtu, sulfur removal 95%, Ca/S 1.8, particulate 0.01 lb/MBtu

e: NO_x 0.3 lb/MBtu, sulfur removal 90%, Ca/S 2.5, ESP particulate 0.03 lb/MBtu

f: NO_x 0.6 lb/MBtu, sulfur removal 90%, Ca/S 1.1, ESP particulate 0.03 lb/MBtu
These represent current NSPS for coal-fired power plants.

g: Low-NO_x burners with 25 ppmv NO_x (at 15% oxygen)

estimated to have the capability of economically improving on the performance required cleaning, and Second-Generation PFBC have outstanding environmental performance. by current and projected future emissions standards. Air-blown IGCC with hot gas The solid waste from these technologies is higher than that from several other advanced technologies, but is lower than that from conventional, coal-fired power plants on the basis presented in the table. Solid waste disposal, and its potential by-product uses are currently developing issues.

Based on the tabulated comparisons, the air-blown coal conversion processes with hot gas cleaning, and Second-Generation PFBC, have the greatest thermal efficiency potential, and have adequate emissions control potential. Air-blown, fluidized bed coal gasification processes with hot gas cleaning (for example, the KRW gasifier, Sierra Pacific, Pinon Pine Project) and Second-Generation PFBC (Air Products, Four Rivers Energy Modernization Project) are scheduled to be demonstrated in Clean Coal Technology Programs, and are appropriate for consideration in the CFATS. Both of these technologies are considered as CFATS because they pose very similar conditions and constraints on the combustion turbine and are both involved in major demonstration programs than will lead to commercialization.

These selected technologies also provide greater challenges to the combustion turbine than other advanced technologies, because: 1) air-blown, hot gas cleaning systems deliver a high-volumetric flow of low-Btu fuel gas to the combustion turbine at a high temperature, requiring large manifolding/combustion systems adapted to high-temperature duty; and 2) hot gas cleaning produces fuel gas conditions with potentially higher contaminant contents than do low-temperature cleaning systems. Successful development of the selected CFATS ensures that adaptation to the other coal-fueled technologies can be achieved with relative ease.

Section 4

ESTIMATE OF CFATS PERFORMANCE AND EMISSIONS

CFATS performance and emissions estimates for IGCC (air-blown, fluidized bed gasifier with hot gas cleaning) and Second-Generation PFBC have been made using prior process studies for these technologies. The power cycle conditions in the prior studies were modified to the conditions of the CFATS, and process material and energy balances were developed to estimate the modified power plant performance. In both cases, significant increases in plant performance were obtained, while environmental emissions were maintained at low levels.

IGCC CFATS DESCRIPTION

An IGCC, CFATS process flow diagram, representative of several types of air-blown, coal gasification plants with hot gas cleaning being developed in Clean Coal Projects, such as the Sierra Pacific, Pinon Pine Project (KRW fluid bed gasifier), the Tamco Power Partners, Tom Creek Project (Institute of Gas Technology fluid bed gasifier), and the ABB CE, Springfield Project (Combustion Engineering entrained gasifier), is illustrated in Figure 4-1. Estimates of plant cycle performance and emissions were made for a specific KRW fluid bed gasification process using process design information reported in a recent DOE/METC study [Southern Company Services, "Assessment of Coal Gasification/Hot Gas Cleanup Based Advanced Gas Turbine Systems, Dec. 1990," DOE/MC/26019-3004].

In the process diagram, coal and a sulfur sorbent, limestone or dolomite, are prepared (sized and dried) for feeding using conventional handling and preparation equipment. The coal and sorbent are pressurized and distributed to the fluid bed gasifier by a commercial feeding system in either dry or slurry form. The gasifier generates a low-Btu fuel gas that has been partially desulfurized by the in-bed sorbent.

The fuel gas is pre-cleaned by conventional cyclones and the captured ash, char and sorbent particles are either recycled to the gasifier or are removed to solid waste processing. The fuel gas is cooled by indirect, high-pressure steam heat exchange, to a temperature of 800° to 1000°F, as is dictated by the zinc-based, sulfur removal process. After cooling, the fuel gas sulfur content is reduced to an acceptable level by a

regenerative, zinc-based, fluid bed sulfur removal process. The sulfur removal process may either produce a sulfur by-product, or may recycle the regenerator sulfur stream to the gasifier, or to solid waste processing. The desulfurized fuel gas then passes through a ceramic barrier filter for final particle removal before entering the combustor. Fuel gas particle content is limited to a total solids content and maximum particle size acceptable to the turbine expander, as well as to environmental standards.

Air provided by the turbine compressor combusts the fuel gas to the desired temperature of 2700°F. The combustor is a dry, low-NO_x design that is closely integrated with the turbine. A portion of the turbine compressor air also is boosted in pressure for gasifier oxidant supply. The combusted fuel gas is expanded in the turbine, and steam is generated in the heat recovery steam generator (HRSG) for the steam bottoming cycle. A portion of the high-pressure, cold reheat steam is consumed in the gasifier, assisting the coal gasification reactions. High-pressure steam is also heated in the fuel gas cooler. The stack gas temperature exiting the HRSG is limited by the gas dew point at its prevailing acid-gas content.

Waste solids from the gasifier, the cyclones and the ceramic barrier filter are treated in a waste process to utilize the waste solids fuel content and sensible heat content, and to render the waste environmentally acceptable.

The coal gasification process chosen for study is the KRW process. It is carried out in a bed of char and ash with added limestone sorbent for fuel gas desulfurization and volatile product cracking. The bed is fluidized by the air and steam required for carbon conversion and temperature adjustment. The ash is agglomerated in the bed to facilitate its removal. The fuel gas leaving the fluidized bed is cleaned hot. The possible cleaning steps include:

- absorption of residual H₂S and alkalis (Na and K compounds carried in the gas) by solid sorbents,
- reduction of the NH₃ content by catalytic decomposition,
- removal of particulates by a filter.

The temperature of the fuel gas between the gasifier and the turbine is lowered for cleaning and for delivery to the turbine at 1000°F. This reduction is accomplished either

by a steam quench or by heat interchange preferably, for best efficiency, with the steam and/or air fed to the gasifier.

The ash and sorbent solids removed from the bed are oxidized with air to recover their carbon content as heat and to convert the sulfided limestone based sorbent to a sulfate, suitable for disposal. This process can be carried out at ambient pressure; and the hot combustion product gases, used for coal preheating and drying and/or for steam generation. The temperature of the process must be carefully controlled to prevent the release of sulfur from the sulfided sorbent as SO_2 . An alternative process carries out the oxidation of the ash and sorbent at pressure with the return of the hot gases to the gasifier. In this instance, the heat is efficiently recovered in fuel production; and the escape of SO_2 is effectively prevented.

SECOND-GENERATION PFBC CFATS DESCRIPTION

The process flow diagram in Figure 4-2 illustrates the general Second-Generation PFBC configuration adapted for the CFATS. Specific plant performance and emissions estimates were prepared for the specific configuration of the technology being developed by the Foster Wheeler Corporation under a DOE/METC supported program [Phase 1, Task 1, Topical Report, DOE/MC/21023-2825, Vol. 1, September 1989].

In the process diagram, coal and a sulfur sorbent, limestone or dolomite, are prepared (sized and dried) for feeding using conventional handling and preparation equipment. The coal and limestone are pressurized and distributed to the carbonizer with a commercial feeding system in either dry or slurry form. The carbonizer generates a low-Btu fuel gas that has been substantially desulfurized by the in-bed sorbent. The carbonizer differs from a gasifier in that it produces a large flow of char that must be combusted separately. The carbonizer fuel gas acts as a topping fuel for the char combustor. Char drained from the carbonizer and captured by the cyclones and ceramic barrier filter is circulated to a fluidized bed combustor. In this combustor, char is burned, sulfur released from the char is captured by the sorbent contained in the solids from the carbonizer, and steam is generated in the fluid bed heat exchanger (FBHX).

The fuel gas and combustion gas streams are pre-cleaned by conventional cyclones. Neither the fuel gas or the combustion gas is cooled before final particle control is

Figure 4-2
Coal-Fueled Advanced Turbine System - PFBC

performed by ceramic barrier filters, and additional sulfur removal is not required. Particle penetration is limited to total content and particle sizes acceptable to the turbine expander. Alkali removal may be required from the fuel gas or vitiated air streams, using, for example, packed bed absorbent.

"Vitiated air" issued from the fluid bed combustor combusts the fuel gas to the desired temperature of 2700°F. The combustor is a dry, low-NO_x design specially configured to utilize the hot fuel gas and the hot, vitiated air. A portion of the turbine compressor air is boosted in pressure for carbonizer oxidant supply. The combusted fuel gas is expanded in the turbine, and steam is generated in the heat recovery steam generator for the steam bottoming cycle. A small portion of the high-pressure, cold reheat steam may be consumed in the carbonizer, preventing coking from occurring. The stack gas temperature in the HRSG is limited by the gas dew point at its prevailing acid-gas content.

Waste solids from the fluid bed combustor, the cyclones and the ceramic barrier filter are cooled to utilize the waste solids sensible heat content. No treatment is required to render the waste environmentally acceptable.

PERFORMANCE AND EMISSIONS ESTIMATES

The performance and emissions of the selected CFATS has been estimated by modifying the process designs found in the Reference Studies for these two technologies. Southern Company Services evaluated, with the M.W. Kellogg Company, Tennessee Technological University, and the General Electric Company, several IGCC process configurations of the KRW gasifier using hot gas cleaning. Case 3 from this study, a nominal 200 MWe plant having bulk sulfur removal with limestone in the KRW, fluid bed gasifier, and zinc ferrite sulfur polishing, was used as the basis for the performance estimates. The Foster Wheeler Development Corporation (FWDC) with several subcontractors, has developed commercial plant designs and performance evaluations for Second-Generation PFBC. A recent evaluation of Second-Generation PFBC, performed by FWDC with a high-temperature turbine, was applied as the basis for the CFATS performance emissions.

Table 4-1 lists the power plant thermal performance for both the Reference Studies and the CFATS cases, along with the steam cycle conditions and the combustion turbine conditions.

The fluidized bed gasification system presented in the reference study has the following unique features:

- The moist coal is dried and preheated at atmospheric pressure prior to feeding into the fluidized bed gasifier. Hot combustion product gases from a combined carbon burnup/sorbent sulfation operation are used in this process and exhausted to the stack.
- The coal feed and the char recycle streams are transported with cooled, cleaned, and compressed fuel product gases. The recycle fraction is not quantified in the flow sheet, but calculations indicate that between 30 and 45% of the fuel product is recycled for coal and other transport. The recycle stream also provides most of the water vapor, steam, required to moderate the operating temperature of the gasifier.
- The product fuel gas is cleaned -- H_2S ; NH_3 ; Na, K, and Cl; and particulate removal or reduction -- and cooled to 1000°F in preparation for recycle and for feed to the turbine. (The order of the various cleaning and cooling operations is not completely specified.) Cooling of the product fuel gas is carried out by a combination of heat exchange, generating steam and hot boiler feed water for the bottoming Rankine cycle, and of steam quench, enhancing the steam content of the product gas for recycle to the gasifier and feed to the turbine.

The air/coal ratio is 3.4 lb/lb. The steam/coal ratio is not directly specified and cannot be accurately calculated because of a lack of information on both the fuel gas recycle and the temperature of the gasifier; it appears to be in the range 0.4 to 0.7 lb/lb. The Ca/S mol ratio for the sorbent feed is 3.0.

Table 4-1 - CFATS Thermal Performance

	IGCC (KRW gasifier)*	Second-Generation PFBC
REFERENCE STUDY		
Steam conditions		
Temperature (F):	1000	1000
Pressure (psia):	1600	2400
GT conditions		
Combustion temperature (F):	2350	2800
Expansion Ratio:		12
Stack gas temperature (F):	280	280
Steam over Gas turbine power:	0.6	0.9
Plant net heat rate - LHV (Btu/kWh):	8211	7010
Plant net efficiency - LHV (%):	41.5	48.7
Gasifier cold gas eff - LHV (%):	72.1	---

CFATS PERFORMANCE

	Modified Process^b	
Turbine Frame	ATS	ATS
Steam conditions		
Temperature (F):	1098	1100
Pressure (psig):	1815	1800
GT conditions		
Combustion temperature (F):	2732	2732
Expansion Ratio:	18	18
Stack gas temperature (F):	208	280
Steam over Gas turbine power:	0.562	0.57
Plant net heat rate - LHV (Btu/kWh):	6800	6690
Plant net efficiency - LHV (%):	~50.0	~51.0
Gasifier cold gas eff. - LHV (%):	86.8	---
Gasifier hot gas eff. - LHV (%):	95.8	---

* Process was modified to incorporate coal drying, carbon burnup, and sorbent processing within the gasifier. Steam used for coal and char transport rather than recycle gas. Fuel gas cooling produced steam fed directly to the gasifier.

A modified fluidized bed coal gasification process has been proposed and evaluated for the CFATS, having these distinct features.

- The moist coal and recycle char are fed to the gasifier in superheated steam. No cooled, cleaned, compressed fuel gas is recycled.
- Burnup of carbon from the ash and sulfation of the spent sorbent are carried out with air at system pressure and the hot gases are routed to the gasifier.
- The product fuel gas is cleaned as previously, but cooling is accomplished in exchangers which provide superheated steam (and perhaps also heated air) for gasification. No steam is exported to the bottoming Rankine cycle.

The air/coal ratio is 3.0 lb/lb; the steam/coal ratio, 0.8 lb/lb. The Ca/S mol ratio is 2. The gasification temperature is 1806°F; the product fuel gas temperature, 1000°F. Material and energy balances have been carried out for this process based on the Illinois No. 6 coal feed selected for the reference study described above. These simplified calculations assume equilibria are attained in the gasifier for the reactions:

The fuel gas quantity and composition have been calculated for this modified fluidized bed coal gasification process. Both the hot and the cold gas efficiencies are significantly increased by the process modifications. Further increases in efficiency, to the extent practical in the design and operation of the plant, might be obtained by:

- increasing the temperature of the product fuel gas fed to the gas turbine;
- reducing the air/coal, steam/coal, and sorbent/coal ratios; and,
- increasing the pressure and reducing the temperature of the gasification process.

The overall performance of a CFATS plant in power generation has been estimated based on the modified fluidized bed coal gasification process described above and on the selected GFATS cycle selected by Westinghouse for development. The gasification study has defined the coal, air, and water input streams and the fuel gas and steam output streams. Combustion calculations have been carried out to determine the quantities of fuel gas and air to reach the specified combustor outlet temperature of about 2700°F. The Westinghouse GFATS cycle calculations have been used to define four work terms:

- compression of the air used in combustion, dilution, and gasification -- assumed proportional to the mols of air;
- compression of the air used in turbine vane, blade, and rotor cooling -- assumed proportional to the mols of hot gases entering the turbine;
- expansion of the air diluted combustion products from the turbine combustor -- assumed proportional to the mols entering the turbine times the quantity $[(\gamma)/(\gamma-1)]$ where γ is the specific heat ratio for the diluted combustion product gases; and,
- generation and expansion of steam in the bottoming Rankine cycle - assumed proportional to the mols of diluted combustion product gases times their specific heat times the temperature difference between inlet and outlet gases.

The gasification and combustion calculations for the gasification process described above have been used to determine the proportionality factors described above and in turn to estimate the work quantities associated with the compressor, expander turbine, and bottoming cycle of a CFATS plant from those of the Westinghouse GFATS. The work of the booster compressor for air feed to the gasifier from the turbine compressor has been

calculated based on an assumed efficiency and inlet temperature. Mechanical, electrical, and windage losses and auxiliary power for the generation section have also been estimated from the Westinghouse GFATS study and auxiliary power for the gasifier and coal feed sections, from the Reference Study, previously cited.

The resulting net overall heat rates and plant efficiencies for the CFATS coal gasification power plants, based on the lower heating value of the fuel, are presented in Table 4-1. The overall plant efficiencies for both the KRW and the revised fluidized bed coal gasification power plant with the Westinghouse proposed advanced gas turbine cycle are 10 to 25% above those of the conventional coal fired power plants.

The Second-Generation PFBC Reference Study was a recent evaluation performed by Foster Wheeler and Gilbert/Commonwealth Associates of a commercial plant using a high temperature turbine. A major modification to this study was a notable reduction in the turbine air cooling needs. The CFATS conditions result in significant performance improvements over the Reference Studies.

Environmental performance estimates are listed in Table 4-2 for the CFATS cases. The same reference coal has been used for the estimation of environmental emissions as was used for the tabulated information in Table 3-2. Comparison is also made with conventional, coal-fired power plants and with conventional, natural gas-fired power plants in the table. The basis of reporting the emissions in this table is "per unit of net power output", lb/hr/MWe, rather than the usual "per unit of fuel energy input", lb/MBtu. A large advantage for the CFATS relative to commercial technology, and relative to the performance of the advanced technologies using current combustion turbines (Table 3-2) is shown in this table.

Table 4-2 - CFATS Emissions Performance

	NO _x	Emission (lb/hr/MW _e)		Particulate	Solid Waste
		SO ₂	CO ₂		
<u>CFATS</u>					
IGCC (O ₂ -blown) ^a	1.4	0.64	1409	5.4	212.3
2nd-Gen. PFBC ^b	1.3	1.55	1366	5.2	190.2
<u>Conventional</u>					
AFBC ^c	2.8	4.45	1959	22.2	257.3
PC/FGD ^c	5.7	4.45	1959	22.2	244.6
Gas Simple-Cycle ^c	0.8	---	1061	---	---
Gas Combined-Cycle ^c	0.7	---	843	---	---

a: NO_x 0.2 lb/MBtu, sulfur removal 98%, Ca/S ratio 1.8, particulate 0.01 lb/MBtu

b: NO_x 0.2 lb/MBtu, sulfur removal 95%, Ca/S 1.8, particulate 0.01 lb/MBtu

c: See Table 2 comments

Section 5

IDENTIFICATION OF DESIGN CHANGES TO GFATS

While the two coal-based power systems differ significantly in their major process conditions, power cycles, process designs and equipment arrangements, both pose a similar set of requirements on the fuel gas combustion and the combustion gas expansion equipment. Both require effective use of the turbine compressor air supply with minimal compressor modifications. With both, a hot, low-Btu fuel gas is generated that must be efficiently combusted, with acceptable NO_x and CO emissions, producing the designated 2700°F combustor outlet temperature, uniformly distributed over the inlet of the turbine expander.

The GFATS consists of several functional components that must be modified for the CFATS: the air compressor, the combustor inlet fuel gas and oxidant gas manifolds, the flow controls, the combustor, the turbine inlet scroll, and the turbine expander. The GFATS compressor can be modified by standard techniques to provide the air requirements for the coal processing steps and for the low-Btu fuel gas combustor. Some 20 to 30% of the air leaving the gas turbine compressor must be boosted in pressure and ducted to the coal gasifier. Customarily, the booster compressor, with associated cooling and heat recovery exchangers, is a device independent of the gas turbine. Low pressure loss takeoffs for gasification air, as well as for turbine cooling air, are required. Also, because higher combustion product flows and higher gas temperatures in the turbine result from replacing natural gas fuel by coal gas, slightly higher air flows may need to be extracted from the compressor for turbine cooling. This is a modification that can be accomplished by available engineering design and evaluation techniques.

A major divergence from the GFATS is the combustor design. The IGCC, low-Btu fuel gas can be efficiently combusted by internal, rich-lean combustor baskets located within the turbine cylinder, much like the GFATS, but adapted to the high temperature fuel gas conditions. The flow of air to the gas turbine combustor is reduced by some 20 to 30% due to the air flow extracted for the coal gasification process; thus, there is less air available for combustor cooling. But the maximum stoichiometric, adiabatic flame temperature associated with coal gas is much lower than that with natural gas. For this reason, the reduction in the quantity of combustor cooling air may not be critical. The lower flame temperature will reduce the formation of thermal NO_x. The volumetric flow

rate of the coal gas is higher than that of the natural gas fuel by a factor from 6 to 9. The temperature of the coal gas is 1000°F; that of the natural gas, 670°F. The volumetric flow of the fuel is thus greatly increased, and redesign of the fuel nozzle and mixing arrangements is required. Flame stability in the combustor does not appear to be a problem because of the high H₂ content of the coal gas fuel. If this larger cylinder exceeds the maximum shipping dimensions, the engine would have to be shipped without the top half.

The Second-Generation PFBC combustor conditions may require that the multiple, internal combustor baskets of the GFATS be replaced by external combustor chambers, as shown in the illustration of Figure 5-1, due to the large size of the combustor chambers required. Two combustion chambers, each with eight combustor modules, would be located externally to the main engine cylinder, one on each side, as shown. Hot, low-Btu fuel gas, and combustion vitiated air, would be distributed to these combustors uniformly to achieve the required combustion performance. The external combustion requires that an inlet scroll be designed, with an appropriate cooling scheme, to introduce the combustion gas into the turbine.

The combustors must be designed with minimal structural cooling, to combust the low-Btu fuel gas efficiently and with acceptable pressure drop, acceptable outlet temperature uniformity, acceptable metal surface temperatures, low CO, soot and unburned hydrocarbons, low conversion of fuel-bound nitrogen to NO_x, acceptable turndown performance, and with multiple fuel capability. (Combustors are being developed by Westinghouse under DOE/METC study Second Generation PFBC Systems R&D contract with Foster Wheeler, DE-AC21-86MC21023.)

The combustion turbine cylinder from the compressor discharge to the turbine inlet would require major design changes for the Second-Generation PFBC case. The casing inlet, manifold/inlet scroll and outlet arrangement would be modified from the GFATS to duct the combustion products by transition liners into a uniform annular flow, as is shown in Figure 5-2. Engineering analysis must be performed, considering heat transfer analysis, stress analysis, pressure drop analysis and computational fluid dynamic analysis. Engine thrusts must be reviewed and thrust bearings redesigned, if required. The combustion turbine bedplate mounting will also be substantially modified, in the Second-Generation PFBC case, from the GFATS. Similar considerations of the combustion turbine casing for

Figure 5-1 Conceptual Dual Topping Combustor Arrangement

Figure 5-2 Topping Combustor Outlet to Turbine Inlet Gas Flow Concept

the IGCC case must be made, but under much less challenging conditions. The substitution of coal gas from the KRW or the modified fluidized bed process for natural gas fuel increases the mol flow of the combustion product gases by some 13 to 24% depending on specifics of gasifier operation. This flow increase and the higher specific heat of the coal gas combustion products, with their higher CO₂ content, increases both the work output from the turbine by 15 to 28% and the temperature of the expanding gases within the turbine -- by as much as 80°F at the turbine exit. The blade design and blade cooling arrangements must be adequate to cover these increased loads and temperatures.

Special consideration must be given to the operation and control of the integrated coal gasification, hot gas cleaning, coal-fired advanced turbine system, CFATS. Operation includes start-up, load follow, and shutdown -- planned and emergency. Control includes maintaining steady optimal operation. Start-up of the plant will probably require special provisions for natural gas firing of the gas turbine(s) -- fuel nozzles and perhaps auxiliary combustors. Emergency shut down, for example on load loss, will require quick acting valves to isolate the gasification and gas cleaning systems from the turbine to prevent overspeed and blow back into the compressor. Load follow and control of the turbine with its integrated coal gasification, hot gas cleaning fuel supply will require coordinated adjustment of the coal, air, and steam feed to the gasifier. A single fuel flow valve, customary for a natural gas fired turbine, is not adequate to provide load follow and to protect the turbine from excessive combustion temperatures. A fuel flow control may need to be omitted due to the high temperatures and flows involved. In this case the coal, air, and steam valves on the gasifier feeds will be required to provide both the turbine and gasifier control functions. Flow controls may be placed in differing positions in the CFATS plant, so that they may provide control over lower-temperature streams located upstream of the major coal processing steps. For example, in Second-Generation PFBC, vitiated air control to the combustor may be achieved by air control to the fluid bed combustor, providing valves that operate at commercially available temperatures. Similarly, over speed protection valves must be supplied for the CFATS that are placed in acceptable locations that may differ substantially from the those of the GFATS. Compressor air bypass, through the turbine start-up burner, to the combustor may be used to cool the expansion gas and promote turbine speed reduction, as is shown in Figure 5-3.

The piping to and from the coal to fuel processing system must be designed to reduce and control thermal expansion stresses and pipe reactions on the turbine cylinder. The

Figure 5-3 Topping-PFBC Process Schematic

requirement for the use of by-pass valves to prevent turbine overspeed in the event of sudden load loss must be studied and the piping arrangement will be evaluated to minimize piping cycle flow pressure losses. Assuming the mass and energy stored in the coal gas system is similar to that stored in the recuperator for the GFATS, the control system functions should also be similar except where changes are required to account for the considerable larger fuel flow. The control concept must be reviewed to identify modifications. Many of the control issues are being evaluated within the current advanced, coal-fuel technology development programs and do not need to be considered in the ATS program.

The turbine airfoil geometry and casing sections themselves will not be substantially modified from the GFATS, although the row 1 vane spacing must be increased to accommodate differences in flow between the GFATS and the CFATS, providing acceptable pressure reduction. The airfoil materials may also be substantially modified. The combustion products will contain vapor and solid/liquid contaminants that are known to induce turbine aerofoil material corrosion: sodium, potassium, vanadium, lead, calcium, lithium, phosphorous, silica, chlorine, iron, copper, and nickel. These may reduce the life of key turbine components and increase system maintenance requirements. Not only must hot corrosion, induced by deposition of slag-like particles and condensable vapors, be

considered, but cold end corrosion due to acidic mists, condensates and slurries must also be considered. While corrosion may be a concern in the CFATS, it should not be any more severe than it is in the current coal-fired turbine systems because the processing steps are at identical conditions, and the turbine aerofoils are cooled to the same temperature levels in both cases.

The effectiveness of hot gas filters should make turbine aerofoil erosion a secondary concern. Particle deposition may be more severe in the CFATS than in the current coal-fired turbine cases because of the higher firing temperature and resulting adherence of particles. Available on-line and off-line airfoil cleaning methods may need to be optimized for the CFATS. Specific turbine airfoil base materials and thermal barrier coatings will need to be specified for the CFATS that are tolerant of the gas contaminants both during steady operation, during off-design conditions, turndown, startup and shutdown transients, as well as during off-line conditions.

It is expected that the material for the main cylinder, horizontal joint, and vertical flange bolting will be the same as used in the GFATS. The hot gas containment system in the Second-Generation PFBC case could present the most critical problem for this design. This containment system represents a large area to maintain at acceptable metal temperatures, control leakages at the juncture to the turbine inlet, and minimize distortion to stay within acceptable limits. Materials would need to be the same as used in state of the art gas turbine combustors and transition pieces, or possibly even using new concepts, such as ceramics, in some areas.

The possible arrangement of the Second-Generation PFBC combustor system into two off-board combustor housings, as opposed to the conventional in line, on-board combustors of the GFATS present some major design and development problems. (As applicable, reference should be made to a Westinghouse study on the generic turbine design to develop a conceptual design of a combustion turbine that would perform in a PFBC, DOE/METC Contract DE-AC21-86MC23167.) The extended surface of the hot gas flow path is much greater in area than would be the surface of the transition pieces in the GFATS. All of this surface must be cooled by compressor discharge air, as shown in Figure 5-3. The cooling required will be much more than can be achieved by surface convection, which has been the conventional way of cooling the transitions. Impingement cooling of ceramic tiles lining the interior of the extended hot gas flow path means a significant amount of compressor discharge air will by-pass the combustion process within

the combustors, thereby reducing the amount of air available for the combustion process, cooling the combustor wall surface, and the profiling of combustion products for uniform turbine inlet temperature for the first row vanes. It is difficult in an off-board combustion system arrangement, to have any real final control of turbine inlet temperature profile, because of the lack of control of the mixing process in the large volume of space between the exit of the combustor and the inlet to the turbine.

Critical structural problems exist that differ from those of the GFATS. Both stationary and rotational parts must consider short-term loading, fatigue, creep, and embrittlement failure mechanisms. These considerations especially must be made for the combustors (primarily thermal fatigue due to overheating and shocking), and the turbine disks, blades, and nozzle vanes. The critical structural problem in the CFATS is thermal stress and distortion caused by temperature differences between the compressor and combustor legs and the mating leg from the turbine cylinder. Also, a similar problem exists for the hot gas duct containment cylinder, and inlet scroll that guides the hot gases into the turbine inlet. An extensive finite element heat transfer analysis will be required to redesign the cylinders, flanging, and the interior hot gas flow system to insure that stress and distortion limits are met.

Section 6

CFATS DEVELOPMENT REQUIREMENTS

The design changes identified in Section 5 provide the basis for devising a development program as described in this section. Conversion of the GFATS to the CFATS will require development test activities in the following areas:

- combustion system
- inlet manifold and scroll ducting from the combustor outlet to the turbine inlet
- turbine deposition and materials selection.

Several changes are required that are expected to be accomplished by standard design procedures and materials selection, and do not require development test activities. These engineering activities are:

- compressor design
- combustor design evaluation
- scroll ducting design evaluation
- turbine expander design
- control.

The combustor outlet gas temperature is approximately 2700°F, and, with an external combustor, this gas is ducted into a scroll which directs the gas to the turbine inlet. Combustion tests will include this scroll as part of the test configuration.

The combustor could be designed either for lean-burn or for rich-lean operation. Both of these are currently used as Westinghouse combustors, with the rich-lean Multi-Annular Swirl Burner (MASB) as shown in Figure 6-1, being developed specifically for Second-Generation PFBC applications (Domeracki, et al, Second Generation PFBC System Research and Development, Phase 2; Topping Combustor Development, Proc. Ninth Annual Coal-Fueled Heat Engines, Advanced Pressurized Fluidized Bed Combustion, and Gas Stream Cleanup Systems Contractors Review Meeting, October 1992, DOE/METC-93/6129). The main combustor elements consisting of cylindrical sections, lend themselves to the use of ceramic cylinders using ceramic materials developed in the parallel materials development section of the ATS program.

Downstream of the exit of the burners is a large volume of space that must have all of its surface cooled to protect the metal housings that separate the compressor discharge air from the hot gases exiting the combustor and entering the turbine. With the combustor outlet temperature being 2700°F, the design challenge is to keep the internal surface temperature from penetrating into the metal support structure. A ceramic tile, or a ceramic composite section may be required.

Turbine deposit is a potential short-term operation concern and the tolerable particulate levels and cleansing methods need to be assessed.

Figure 6-1 Multi Annular Swirl Burner

OBJECTIVE

The development activities will lead to a combustion system that achieves efficient combustion of the hot, low-Btu fuel gas, while meeting all emission targets and having satisfactory life and maintenance of components. The system will achieve a satisfactory pattern factor of the hot gas delivered to the turbine vanes with a minimum of scroll pressure drop and leakage loss. The development program will utilize advanced ceramic materials for key components where this is necessary and feasible, and will identify other key materials of construction.

TECHNICAL APPROACH

The development activities will perform the necessary combustion, heat transfer, and mechanical analyses needed to produce an effective design of the combustor and related gas distribution components. Development tests and test conditions for the necessary design evaluations will be determined. Appropriate test equipment and facilities will be fabricated, installed, and tested to evaluate performance. Significant aspects of the development program are:

Combustor emissions -- The hot, low-Btu fuel gas will contain fuel-bound nitrogen (ammonia) and a rich-lean combustor design, such as the Westinghouse MASB adapted to the extremely high combustion temperature, will be required to meet NO_x, CO, and unburned hydrocarbon emissions. The MASB has been under development for Second-Generation PFBC at current combustion turbine temperatures, and design and testing techniques have been established that can be applied in the ATS program.

Combustor and scroll materials -- Metal structures, cooled by inlet combustion/compressor air may be used, and these may require thermal barrier coatings. With the vitiated air temperature in the CFATS ranging from 1400 to 1650°F, the metal structure design is extremely challenging. The option of using ceramic tiles, or an entire ceramic composite wall structure is an important option that will also be evaluated.

Turbine materials and deposition -- Base materials and thermal barrier coatings will be evaluated and selected for compatibility with the projected expansion gas contaminants to meet economical component life and maintenance requirements in the CFATS.

Deposition of coal-based ashes on the turbine vanes and blades will be characterized and cleaning methods assessed.

Fuel gas, combustion air handling -- The CFATS uses fuel gas at temperatures ranging from 1000° to 1600°F, and combustion air/vitiated air ranging from 827° to 1650°F. Piping designs will need to be specified for this high temperature duty as refractory-lined piping with high-alloy metal liners. This aspect of the system is not a major part of the development efforts.

Flow control -- Commercial control valves of a size suitable for the CFATS application are available for temperatures up to 1300°F. For higher temperatures, the valves must be specially designed with advanced internal cooling features and materials, and proof tested. Alternatively, they must be located at points of lower temperature and the combustion turbine control strategy adjusted. This aspect is not a major part of the development effort.

Flow distribution -- The manifolding of fuel gas and combustion air to the multiple combustors, and the scroll distribution of combustion gases to the turbine will be designed to provide uniform flow distribution over the range of plant operation with minimum pressure losses, and with acceptable temperature pattern factor to the turbine.

Structural design -- Finite element heat transfer/stress calculations will be applied to the integrated CFATS to ensure feasible design arrangement.

Testing -- To minimize risk, testing of key components will be performed first at low-pressure (about 2 atmospheres) and full temperature conditions before progressing to full-pressure tests.

WORK STATEMENT

Task 1. CFATS design: Perform a conceptual design of a commercial-scale, CFATS for both the IGCC and the Second-Generation PFBC cases. The design should include:

- the compressor
- the combustor
- scroll ducting
- the turbine expander
- the control system

Task 2. Low-pressure test rig. Design a low-pressure, full-temperature, subscale combustor basket and cascade test rig for testing under IGCC and Second-Generation PFBC conditions at a facility having suitable test capabilities. The test rig will incorporate integrated manifolding, turbine transition duct or, inlet scroll, and vane cascade sections. Advanced materials testing will be incorporated as appropriate. Construct the test rig and specify the test plan and test requirements.

Task 3. Low-pressure rig tests. Conduct low-pressure rig testing at the selected test facility, confirming design performance and the effectiveness of special features and materials for both IGCC and Second-Generation PFBC conditions. Measure flow distributions, pressure drops, temperature distributions, surface temperatures; heat transfer coefficients, and cascade particle arrival and deposition rates. Evaluate the test results and compare them to the CFD projections and other applied design criteria. Scale the test performance results to high-pressure conditions.

Task 4. Full-scale module rig design. Design a full-scale combustion chamber for testing at a facility having suitable test capabilities, under simulated IGCC and Second-Generation PFBC, CFATS conditions. Incorporate in the test rig design a simulation of the containment manifold and turbine transition duct or inlet scroll that meets all design constraints and requirements. A turbine cascade will be included to examine turbine deposition and cleaning issues, and to subject materials to relatively short-time exposure. Fabricate the test equipment, construct the test facility and structure the test program.

Task 5. Full-scale module rig test. Conduct full-scale combustor chamber/manifold/transition duct or inlet scroll testing at the selected facility, confirming design performance. This test should be conducted as a slip stream facility at an IGCC or Second-Generation PFBC plant. Evaluate the test results and compare them to the CFD projections and other design criteria applied.

PROGRAM SCHEDULE

The program schedule is shown in Figure 6-1. The duration of each task is indicated in the figure. The overall program duration is 51 months, with the schedule being arranged with each task completed in series. Some tasks could overlap to shorten the overall program duration. One of the key schedule issues is the identification of suitable and available sites for the testing.

Figure 6-2 - GFATS Program Schedule

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