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**Identifying Technology Barriers in Adapting a
State-of-the Art Gas Turbine for IGCC Applications
And an Experimental Investigation of
Air Extraction Schemes for IGCC Operations**

Final Report

**Tah-teh Yang
A.K. Agrawal
J.S. Kapat**

June 1993

Work Performed Under Contract No.: DE-AC21-89MC26041

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

**By
Clemson University
Department of Mechanical Engineering
Clemson, South Carolina**

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ABSTRACT

Under contracted work with Morgantown Energy Technology Center, Clemson University, the prime contractor, and General Electric (GE) and CRSS, the subcontractors, made a comprehensive study in the first phase of research to investigate the technology barriers of integrating a coal gasification process with a hot gas cleanup scheme and the state-of-the-art industrial gas turbine, the GE MS-7001F. This effort focused on (1) establishing analytical tools necessary for modeling combustion phenomenon and emissions in gas turbine combustors operating on multiple species coal gas, (2) estimating the overall performance of the GE MS-7001F combined cycle plant, (3) evaluating material issues in the hot gas path, (4) examining the flow and temperature fields when air extraction takes place at both the compressor exit and at the manhole adjacent to the combustor, and (5) examining the combustion/cooling limitations of such a gas turbine by using 3-D numerical simulation of a MS-7001F combustor operated with gasified coal.

In the second phase of this contract, a 35% cool flow model was built similar to GE's MS-7001F gas turbine for mapping the flow region between the compressor exit and the expander inlet. The model included sufficient details, such as the combustor's transition pieces, the fuel nozzles, and the supporting struts. Four cases were studied: the first with a base line flow field of a GE 7001F without air extraction; the second with a GE 7001F with air extraction; and the third and fourth with a GE 7001F using a Griffith diffuser to replace the straight wall diffuser and operating without air extraction and with extraction, respectively. Because the experiments provided only discrete measurements, a 3-D Navier-Stokes solver was used to supplement the additional flow information. The computed results were validated with measured data. The results indicate that air extraction from the manholes at the wrapper will cause flow redistribution around the combustor and the transition pieces, which could lead to the increase of the temperature pattern factor in the expander inlet and cause the transition pieces not to receive adequate cooling. However, when extraction is applied at the inlet of the Griffith diffuser, there is no adverse flow redistribution. At 20% through flow extraction, the overall total pressure loss was reduced by 36% when air was extracted at the diffuser instead of at the manholes at the wrapper. With use of the Griffith diffuser, potentially one percentage point in overall cycle efficiency for IGCC operation could be improved. The sink effect of the combustor bypass holes on the flow field in the prediffuser and the dump diffuser existed in both schemes of air extraction. Once the detailed flow field in the dump diffuser is understood, one may design the Griffith diffuser accordingly to minimize the total pressure loss and to further improve the overall cycle efficiency.

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1.0 INTRODUCTION

It is generally agreed that the current rate of growth of electric power demands will continue beyond the year 2000. Many of the current power generating facilities will be obsolete by that time. Therefore, new systems must be installed to replace the old and to provide added capacity for the increased load. There is significant consensus that the Simplified Integrated Gasification Combined Cycle Systems (IGCC) would be an important element of the new power supplies. The two principal reasons are that (1) the Department of Energy's (DOE) hot gas cleanup program has made it possible to use domestic coal as fuel in the power plants, thereby reducing the uncertainties related to the availability and price of distillate fuel and (2) there is an economical advantage of potentially reducing the capital cost per kilowatt installed.

Clemson University's participation in DOE's Morgantown Energy Technology Center R&D programs in IGCC began in 1988 while evaluating the commercially available combustion computer codes and while collaborating with GE's R&D center on the existing LBtu gas combustion data. However, Clemson University's continuous experimental and computational research efforts in internal flows, particularly in the diffuser flows, have been ongoing for more than 30 years.

The contracted research conducted at Clemson University and reported herein on air extraction and LBtu coal gas combustion in gas turbines for IGCC systems consists of two major phases covered under the contracted research titles: "A Study of Air-Blown Coal Gasification System with a High-Performance Gas Turbine" and "An Experimental Verification of a Compressor Diffuser Flow Field with Air Extraction in a State-of-the-Art American Made Industrial Gas Turbine for IGCC Systems."

The present concept for developing an IGCC system involves utilizing the existing technology for all the subsystems which are integrated into an air-blown hot gas cleanup IGCC system, hereinafter referred to as air-blown simplified IGCC. The guiding principle is to keep the compressor and expander intact if possible. However, issues arise when the subsystems must be integrated and the equipment interfaced. We found that equipment design modifications are necessary. In some incidents, methodology and tools for engineering development and research require examination.

Because the simplified IGCC system requires that a fraction of the air from the compressor be extracted and fed to the gasifier, the choice of extraction site becomes an issue. Structurally, the most acceptable site of extraction is at the engine wrapper or the manhole. Our experience suggests that when the amount of extraction at the manhole is large enough to meet the need of the simplified IGCC system, the induced cross flow around the combustor can and transition pieces would be enough to cause an adverse impact on the cooling scheme of the transition

pieces and the pattern factor of the hot gas entering into the turbine nozzles. An approximated 2-D computer simulation confirmed our speculation. The results of that investigation conclude that air extraction through manholes in a GE 7001F gas turbine causes nonuniformity of the impingement flow rates around the transition pieces. This nonuniformity adversely affects the cooling scheme of the transition piece.

However, one of the alternative extraction sites to the manholes is the compressor diffuser inlet. A class of curved wall diffusers, known as Griffith diffusers, use boundary layer removal at the diffuser inlet and are highly effective in converting flow kinetic energy to pressure. This feature provides a natural solution to the need of air extraction for simplified IGCC. Therefore, an extensive experimental program was implemented as the second phase of research. A 35% scale cool air test model was built similar to GE's 7001F for mapping the flow region between the compressor exit and the expander inlet.

Four cases of studies were conducted, which included 1 base line flow field of the GE 7001F without air extraction and 3 cases of the GE 7001F. Those 3 cases included 1 with extraction and the other 2 with a Griffith diffuser replacing the straight wall diffuser of the original 7001F design operating with and without extraction, respectively. The emphasis was focused on the following issues:

- (1) The air-flow distribution around the combustor and transitions pieces
- (2) The pressure drop in the air extraction path, including the manifold and collection branches
- (3) The total pressure losses in the compressor prediffuser and dump diffuser
- (4) The sink effect of the combustor bypass holes on the flow field in the prediffuser and the dump diffuser

The first issue concerns the cooling of the transition pieces and the pattern factor of the hot gas entering the turbine nozzles. The second issue provides the information regarding the cost of performing extraction in terms of the pressure drop. The last two issues relate to the potential improvement in the loss reduction of that part of the gas turbine. Recently, DOE announced Advanced Gas Turbine Systems Research's (AGTSR) program. The findings of the second and third issues could contribute significantly to the objectives of AGTSR in improving the combined cycle overall thermal efficiency.

2.0 ANALYSIS TO PREDICT COMBUSTION AND FUEL NITRIC OXIDE

The air-blown simplified IGCC system offers clean use of coal in a high-efficiency power cycle. In the concept coal is gasified in a high-pressure, air-blown gasifier. Particulate matter is removed from the gaseous fuel through cyclones and ceramic filters, and sulfur-bearing gases are absorbed with a hot gas cleanup system. The LBtu coal gas is burned in a gas turbine combustor.

In a simplified IGCC system, air for coal gasification is bled from the gas turbine compressor. This air is returned to the gas turbine as a constituent of the fuel. If the fuel flow rate increases, which is required to obtain the desired energy release within the combustor, the characteristics of air and fuel mixing may change. Such a change will necessitate combustor modifications. Furthermore, unlike cold gas cleanup systems, which remove most fixed nitrogen from the gaseous fuel, hot gas cleanup systems allow gaseous nitrogen compounds to be passed through and carried into the combustor. In combustion a fraction of the nitrogen can be oxidized to various oxides of nitrogen, primarily nitric oxide, NO.

In recent years multi-dimensional flow calculations, both reacting and non-reacting, have augmented empirical design procedures commonly used in the gas turbine industry. In an earlier phase of this project, several computer codes were evaluated for LBtu gas application (Yang et al., 1990). None of those codes had all of the required features. That is to say, they did not have comprehensive models for combustion that could incorporate effects of turbulence, nor did they have the capabilities to predict pollutants, such as fuel NO_x, in industrial gas turbine combustors operating on LBtu coal gas.

In developing the computer codes, the following were our objectives:

- to modify computer code(s) that were previously evaluated as appropriate for modeling combustion of LBtu gas from an air-blown coal gasifier
- to describe analytical procedures for the modifications and to provide instructions for using the computer codes to study combustion phenomena at the gasifier-turbine interfaces in an IGCC system
- to determine the extent to which the computer codes can replicate available experimental data
- to further modify computer codes to model emissions
- to predict emissions for the IGCC systems as a function of process and combustor design parameters

- to recommend test programs to obtain additional experimental data for increasing confidence in the methods developed

The combustion models, based on fast-reaction limit, use Favre-averaged conservation equations with the κ - ϵ model of turbulence. Effects of turbulent fluctuations on chemistry are described statistically in terms of the mean, variance and probability density function (assumed to be β -distribution) of the mixture fraction. A 2-reaction global mechanism is used to describe how fuel nitrogen is oxidized.

These models have been added to the multi-dimensional computational fluid dynamics code PHOENICS. Both 2- and 3-D simulations can be made with PHOENICS. PCGC-2 (Brigham Young University), a 2-D combustion code, has also been adapted for fuel nitric oxide calculations in axisymmetric combustors operating on LBtu coal gas.

The code modifications consist of a collection of subroutines to calculate fluid properties and species concentrations based on chemical equilibrium, including the effects of turbulence. Additional coding was done to solve transport equations for the mixture fraction and its variance, nitrogen species and so forth. Nearly 2000 lines of FORTRAN instructions have been added to the original code. Combustion and fuel NO models are accessible through specific instructions coded in the input file.

The code is applicable for 2- and 3-D calculations in Cartesian or polar coordinate systems. Nothing inherently limits the number of combustor inlets or outlets. The output, consisting of velocities, temperature and species concentration fields, can be examined using graphical post-processors during computations.

First, a well-established combustion experiment was modeled to illustrate accuracy of the computational procedure. The centerline axial velocity is under-predicted in much of the flame, although there is better agreement towards the end of the flame. In spite of the differences in the axial velocity, centerline density correlated well with the experimental data in most of the flame region.

Second, a GE test (Lawson, 1985, Beebe and Blanton, 1985, Blanton and Smith, 1985) was modeled. GE's tests with LBtu gas were intended to evaluate material issues. Therefore, these tests lacked detailed thermal fluids measurements. Only a limited amount of 1-D data could be compared with analytical predictions. The combustor liner was a slightly modified GE MS-6000 production liner. Two types of approximations modeled the geometric configuration of the combustor, namely axisymmetric and 3-D.

Essentially the same mass averaged temperature distributions were obtained with axisymmetric and 3-D calculations, while the computed pattern factors and the liner wall temperatures

for the two differed significantly. Complete combustion was predicted with strong swirl at the fuel and air inlets, a result supported by GE's test data. The predicted maximum liner wall temperature correlated well with the experimental data, while the predicted maximum exhaust gas temperature differed by 120 degrees K. The maximum flame temperature was well below 2,000 degrees K, indicating that the thermal NO_x may be insignificant.

The first phase of this work is a parametric study of the nitric oxide formation predicted by PCGC-2 for a simplified, axisymmetric combustor geometry. The main findings for the fuel nitrogen conversion included (a) an increase with inlet fuel and air swirl numbers up to ± 1.0 , (b) a decrease with increasing inlet fuel nitrogen concentration, and (c) a decrease with increasing fuel input to the combustor. The overall nitrogen conversion ratio varied from 35 to 86%, which is in the same range as experimental values reported in literature about combustion of LBtu fuels.

Combustion calculations indicate that a 2-D model is limited in modeling gas turbine combustors. The principal shortcoming is its inability to accurately simulate the penetration and mixing of the dilution jets using an axisymmetric geometry. The 3-D model developed for this work predicted nitric oxide emissions for the GE MS-6000 gas turbine combustor. The predicted conversion rate for the 3-D simulations was higher than the predicted conversion rate for 2-D simulations.

The computer codes developed during this project enable numerical predictions to be made in 3-D industrial gas turbine combustors using multiple species gaseous fuel. No inherent limitations have been imposed on the number of inlets or outlets. Three-D simulations overcame drawbacks of the simplified 2-D simulations which predicted a highly localized flame, high pattern factors and low liner wall temperatures.

A model to predict fuel nitric oxide was also added. The percentage conversion decreased when fuel nitrogen concentration increased. This finding has been reported in literature. Three-D predictions of nitrogen conversion rates were somewhat higher than those for the corresponding 2-D predictions.

So far, the present effort has shown that the overall agreement between numerical predictions and measured data is good to excellent. However, detailed combustion measurements, especially with LBtu gas, are rather limited in rendering adequate confidence in numerical predictions.

In the future DOE sponsored combustion experiment programs should encourage direct measurements so combustor inlet data will be adequately documented. Whenever possible, in-situ temperature and concentration measurements should be made within the combustor, at the combustor exit, and at the exit of the transition piece. Additional data will reduce uncertainties

about the boundary conditions specified at the inlets and will help establish more credible numerical predictions.

3.0 PERFORMANCE EVALUATION OF AN IGCC POWER PLANT

To study high-efficiency gas turbines, the full- and partial-load performance of an air-blown IGCC plant was prepared. The IGCC configuration used a high-efficiency gas turbine integrated with a Lurgi fixed-bed gasifier and other auxiliaries. Dust and sulfur were removed prior to supplying the high temperature gas stream to the gas turbine.

The study established the following estimated performance:

	<u>100% Load</u>	<u>50% Load</u>
Gas Turbine Output (kW)	169,859	84,929
Steam Turbine Output (kW)	65,950	39,112
Generation Losses (kW)	-3,066	-1,613
Gross Plant Output (kW)	232,743	122,429
Parasitic Power Loss (kW)	-9,640	-5,430
Net Plant Output (kW)	223,103	116,999
Heat Consumption (In million Btu per hour - HHV basis)	1,814	1,023
Plant Heat Rate (In Btu per kilowatt- -hour-HHV basis)	8,129	8,742
Efficiency (%)	42.00	39.04

The results of the study show that the air-blown IGCC-cycle-coal-pile to bus-bar thermal efficiency is 42%. Opportunities for improvement in the IGCC performance include increasing the carbon utilization in the cycle and using the energy of the waste gas stream leaving the sorbent regeneration system of the hot-gas cleaning system.

4.0 EVALUATION OF GAS TURBINE MATERIALS

We evaluated the expected performance of the current GE MS 7001F hot section materials in a LBtu air-blown IGCC system. According to our research, no material problems specific to the IGCC cycle are expected if the present fire temperature, 1260 degrees C (2300 degrees F), is maintained and if the LBtu gas is cleaned. However, detailed examination and maintenance of the gas cleanup system are essential. In this evaluation we determined whether stress, temperature, and erosion/corrosion potential require the use of alternative materials. We did not address how those factors might limit the MS-7001F gas turbine's current performance, nor did we address how this performance might be enhanced. Rather, we focused our evaluation on whether altering the fuel composition from natural gas to a LBtu air-blown coal gas would alter the response of combined cycle gas turbine materials.

We assembled the data required for this task from available literature and from consultations with GE-Schenectady, GE-Greenville and suppliers of selected materials. CRS Sirrine served as subcontractor on this task.

Various authorities stated that LBtu coal gas can be cleaned to "whatever level the turbine manufacture specifies." This statement, however, presupposes that the cost of gas cleanup is not prohibitive, which is an economic benefit analysis beyond the scope of the current study. Furthermore, this statement assumes that the gas cleanup system will not suffer a catastrophic failure or that a back-up natural gas system is available if the gas cleanup system fails. Assuming that gas cleanup is available, the combustion environment within the IGCC turbine should be no worse than that typically associated with natural gas combustion. On this basis, and assuming that the firing temperature is limited to 1260 degrees C (2300 degrees F), no materials problems specific to the gasification combined cycle are expected.

Moreover, maintenance of a superclean fuel system should allow an increase in the firing temperature beyond 1260 degrees C. Increasing the firing temperature by 50 degrees C will cause a 1 to 2 % increase in thermal efficiency. It is anticipated that this increase in firing temperature can be achieved through substitution of advanced materials and process techniques for hot section components in which hot corrosion considerations can now be eliminated because of the availability of superclean fuels. Oxidation resistance remains the sole environmental limiting factor in materials selection and manufacture.

Recent evidence does suggest, however, that uncombusted tar by-products may be included in the cleaned LBtu coal gas being supplied to the gas turbine. Subsequent combustion of these vapors could cause enhanced sulphur levels and decreased turbine bucket hot corrosion performance. The amount and composition of the uncombusted tar vapor are presently unknown.

Because of the serious impact that their presence might have on the lifetime of a gas turbine component, both under normal and more advanced firing conditions, a vigorous effort must establish the extent to which tar vapors will be present in LBtu coal gas.

5.0 AIR EXTRACTION FROM A GE MS-7001F COMPRESSOR DIFFUSER

In an IGCC system, a gas turbine can effectively burn LBTu coal gas if part of the compressed air is extracted and if the combustor is redesigned. Two possible sites can bleed the compressed air from the GE MS-7001F gas turbine (i) the prediffuser immediately downstream of the compressor and (ii) the manhole flanges next to the combustor dilution zone. An efficient scheme of extracting air should reduce the loss of compressor discharge pressure and should minimize flow asymmetries in the combustor. While lower pressure losses are important in attaining a high-overall gas turbine efficiency, the symmetric distribution of air around the combustor cans must occur to achieve proper air-fuel mixing inside the combustor and to avoid hot spots on the combustor liner.

Therefore, we evaluated schemes for extracting air from the GE MS-7001F compressor discharge. We also determined air flow processes that reduce pressure losses and minimize flow asymmetries in the compressor discharge/combustion wrapper area. To do so, we compared a Griffith diffuser to the existing manhole flanges to evaluate potential sites for extracting gasifier air flow. The Griffith diffuser was designed to optimize performance, applying viscous flow calculation in conjunction with a trial-and-error procedure.

A typical Griffith diffuser exhibits the following: a low pressure inlet region, a slightly favorable wall pressure up to a slot region, a sudden rise in pressure across this slot region, followed by a slightly favorable wall pressure region towards the exit of the diffuser. Boundary layer suction helps to achieve the pressure jump across the slot. Extraction serves as an integral part of the Griffith diffuser.

The Griffith diffuser design was based on solutions of fully elliptic Navier-Stokes solver for turbulent flows. The compressed air is extracted through a suction slot which is located on the diffuser's curved outer wall. This curvature of the outer wall serves two purposes: it prevents flow separation and it improves the overall performance of the diffuser. Both of these desired effects are achieved when air flow accelerates through the suction slot and when the pressure along the diffuser wall, downstream of the suction slot, remains nearly constant. The suction slot and outer wall geometries required to achieve these effects were determined by a trial-and-error procedure. The diffuser's performance was further improved by extracting 6% of the compressed air through a slot at the inner wall which was kept straight because of structural constraints. The diffuser arrangement was relatively insensitive to upstream distortions in the velocity profile.

Air extraction through the manhole fails to limit the pressure losses since the manhole flanges are located at the downstream end of the compressor discharge/combustor wrapper area. Pressure recovery could be maximized with the Griffith diffuser arrangement for air extraction.

A lower compressor discharge pressure loss will cause the gas turbine to be more efficient. In the GE MS-7001F gas turbine, approximately 50% of the turbine output is used by the compressor. Assuming that the compressor discharge pressure loss is 2% of the total pressure, we estimate that extracting air using a Griffith diffuser would increase the gas turbine efficiency by approximately one percentage point over that where air is extracted through the manhole.

Since the Griffith diffuser allowed control of velocity profile at the exit of the prediffuser, symmetric air flow around the combustor was assumed when the Griffith diffuser extracted gasifier air. Asymmetric air flow around the combustor was anticipated, especially in the dilution zone when the gasifier air was extracted through manhole flanges. This asymmetric air flow in the dilution zone could occur because of the close proximity of the manhole flanges to the combustor dilution zone. The precise magnitude of the flow asymmetry is difficult to estimate because of geometric complexities and interactions between compressor discharge and combustor flows. However, by prescribing asymmetric air flow through liner cooling and dilution holes, mixing in the combustor can be assessed quantitatively.

In this study, asymmetric air flow was assumed to influence the combustor dilution zone only. Computations were done for three cases, one symmetric and two asymmetric air flow distributions. Asymmetry of the flow is characterized by how air is redistributed through the dilution and cooling holes. The information below specifies mass flow rates through each of the dilution holes in terms of the normal air amount:

Dilution Hole	% of normal air amount		
	Case 1 (Symmetric)	Case 2 (Asymmetric)	Case 3 (Asymmetric)
1, Next to the manhole	100.00	75.0	50.0
2, Left of hole 1	100.00	87.5	75.0
3, Furthest away from the manhole	100.00	150.0	100.0
4, Right of hole 1	100.00	87.5	75.0

Boundary conditions at the inlet (in the axial direction) of the dilution zone were established from CRSS's results with a 60-degree combustor sector. For all cases, the overall temperature pattern remained essentially the same, except for the temperature near the dilution hole 1, the one closest to the manhole flange. This temperature increased with increasing air flow asymmetry. The results are summarized in the following columns:

	Case 1 (Symmetric)	Case 2 (Asymmetric)	Case 3 (Asymmetric)
Dilution Hole			
Combustor Exit Temperature, K			
Average	1,530	1,522	1,515
Maximum	1,820	1,820	1,820
Maximum Liner Temperature, K			
Near Dilution Hole 1	1,270	1,360	1,380
Pattern Factor	0.33	0.34	0.35

These results indicate that the air flow asymmetry had a minor effect on the combustor exit pattern factor. However, the maximum liner wall temperature increased as the dilution hole next to the manhole flange was deprived of air. In CRSS's study of combustion and cooling limitations in the GE MS-7001F combustor, which operates on LBtu gasified coal, six fuel nozzle/six dilution hole approximation was used. A similar rise in local liner temperature occurred because of manhole extraction.

Air extraction with a Griffith diffuser causes a lower pressure drop, which in turn, increases the gas turbine efficiency by one percentage point over that where air is extracted through manhole flanges. The flow asymmetry, anticipated when gasifier air is extracted through the manhole, minorly affected the combustor pattern factor. However, hot spots developed on the combustor liner when the dilution and cooling holes were deprived of air.

After comparing existing manhole flanges to a Griffith diffuser as potential sites for extracting the gasifier air flow, we concluded that only the Griffith diffuser causes lower compressor discharge pressure loss without affecting either the liner wall temperature or the air-fuel mixing within the combustor. These conclusions are based on detailed analytical predictions and engineering estimates.

Based on our studies, we recommend two experimental programs: one to validate analytical calculations in the compressor diffuser (in calculations, asymmetry of the flow caused by air extraction from the manhole is characterized by the redistribution of air through the dilution holes) and the other to determine the extent of flow asymmetry when air is extracted from the manhole.

6.0 GAS TURBINE COMBUSTION AND COOLING SYSTEMS OPERATING ON LBTU GAS

In addressing issues related to integrating high-efficiency gas turbines with air-blown gasification technology, we provided exhibits of the 3-D numerical analysis of a simplified model of the GE MS-7001F combustor. Results of the numerical analysis indicate that a typical LBTu gas from a Lurgi, air-blown, fixed-bed gasifier sustains combustion. However, the efficiency and pattern factor of the standard MS-7001F combustor indicate it is unsuitable for LBTu gas fuel. The data indicate a need for a LBTu gas combustion development program. The cooling system is adequate if a firing temperature of 2270 degrees F is acceptable. To raise the firing temperature, more planning is required to prepare the combustion development program. Prior to implementing the development program, a target firing temperature, design combustion gas water content, and combustor air flow need to be established. Providing an adequate cooling system to support the LBTu gas combustor development program is feasible, but requires its own development program. Results from the numerical model of the MS-7001F combustor show a need for a development program for LBTu gas combustion. The development program should establish a target firing temperature, a design fuel water content, and a design combustion air flow prior to program initiation. The program should also address the cooling air flows required to compensate for the higher gas specific heat and temperatures of the combustion products.

7.0 POTENTIAL PROBLEMS, ALTERNATIVES, AND RECOMMENDATIONS FOR SUBSCALE TESTING

Based on the results of the aforementioned studies, some of the potential problems have been identified which could adversely affect the integrating of the coal gasification process with a hot gas cleanup scheme and the state-of-the-art industrial gas turbine, the GE MS-7001F, and the air-blown simplified IGCC system as an attractive, commercially viable system.

Furthermore, identifying these problems have helped us to understand the degree of commercial readiness of the IGCC system configuration and to examine other options or alternative designs and procedures. Our goals were

- to delineate the potential problems associated with the external systems and the potential problems internal to the gas turbine created by the use of coal gas
- to suggest material and design alternatives that might alleviate the potential problems
- to recommend subscale test programs for obtaining necessary data and/or providing confidence in the analysis

Whenever possible numerical results from the combustion and air extraction models performed under this contract were used to illustrate potential problems internal to the gas turbine. Most external subsystems were evaluated by the criteria established from performance, maintenance, control and construction considerations and data from published reports.

A Clemson materials scientist concluded that at a current reduced operation temperature of 2270 degrees F, no problems are expected in the materials area.

Other Clemson researchers observed circumferential hot spots on the combustor liner. These hot spots developed because of the current geometric arrangement of dilution holes and fuel nozzles in the GE MS-7001F. This arrangement included 4 dilution holes 90 degrees apart circumferentially and 6 fuel nozzles 60 degrees apart. Therefore, 2 diametrically opposing spacings between nozzles received good penetration of dilution air where the other 4 spacings caused the hot flames to deflect toward the liner. Numerical results also showed the presence of unburned carbon monoxide and hydrogen at the exit plane of the combustor. The incomplete combustion of the gaseous fuel constituents was supported by the calculated averaged temperature at the exit plane. The exit temperature was approximately 120 degrees F below the temperature, which corresponded to complete combustion. This phenomenon could be because of the high through velocity of the gaseous fuel emitting from the nozzles. It could also be because of inadequate mixing, or because of a combination of both causes. Clemson researchers

also observed that the NO level at the combustor exit was only marginally acceptable. Air extraction for coal gasification via manholes could deprive dilution air locally and, in turn, lead to hot spots on the combustor liner.

Because of the system performance study, CRSS engineers reviewed 11 external subsystems and discussed 22 associated problems. From the combustion/cooling limitation study, 8 additional problems arose. Among all problems, the following 3 are considered critical:

1. There is no quantitative information in the dynamic response of the related subsystems under transient operation, such as during generator breaker trip and compressor trip.
2. The external system configuration studied used a 3-way flow control valve to bypass LBTu coal gas to flare when the generator breaker trips. At the present time no commercial 3-way valve that meets the system's needs is available.
3. The presence of tar vapor in coal gas can be troublesome even if the vapor is only a very small percentage. If the tar vapor condenses, it deposits over surfaces and inhibits operation which impacts performance, decreases reliability and increases maintenance costs.

In addition, CRSS engineers further rated the following 10 problems as less critical but still significant. These problems, however, can be overcome.

1. air extraction manifold and compressor casing thermal stresses
2. efficiency of the booster compressors
3. online gas turbine compressor water washing
4. coal fines
5. gasifier lock hopper
6. carbon lost in hot gas particle separation
7. temperature control to prevent tar condensation
8. refractory lining for zinc ferrite sorbent bed
9. handling tar oil and alkali metals in regeneration process
10. LBTu gas control valve, gas supply piping and nozzle in conjunction with tar condensation

The combustion liner hot spots can be corrected by using 6 dilution holes instead of 4. An increase in the fuel nozzle flow area may reduce through velocity. An increase in fuel swirl may enhance mixing between fuel and oxidizer. Either of these two alternatives or a combination of both may eliminate incomplete combustion. A 2-stage combustion, along with selective catalytic reduction, may be necessary to achieve low NO emissions. An air extraction scheme via a Griffith diffuser design may eliminate liner hot spots due to air extraction.

A study should be conducted to determine the dynamic response for subsystems during the generator trip transient. The results of a transient study could also provide necessary specifications for the development of an axial compressor to replace the 2-stage centrifugal compressor presently assigned as the booster compressor.

A 3-way, bypass valve development program may be implemented with valve manufacturers so that the bypass valve will become a commercially available item when the simplified IGCC system of the configuration is constructed. A temperature control system must be developed to reliably maintain the LBtu gas temperature above 1000 degrees F. This system is important in the control of tar condensation in the downstream equipment.

Insertion of a quenching process to remove tar is used with synthetic fuels. It has the added benefit of removing fuel bond nitrogen from the gas stream. However, the quenching process sacrifices sensible heat from the gasifier's gas stream. An additional study would be required to integrate the quenching system into the air-blown IGCC system.

In addressing materials and design alternatives, 16 topics impact operation. Of these topics presented, 4 are about maintenance and 5 are about performance.

An experimental program was recommended to involve a model of a GE MS-7001F compressor discharge region. Clemson University researchers recommend this experimental program for two reasons:

1. to validate analytical predictions and to demonstrate validity of the designed Griffith diffuser for air extraction
2. to determine the extent of flow asymmetry around the combustor when gasifier air is extracted through the manhole flanges

In addition, Clemson University has identified areas requiring further research that would permit clean combustion of LBtu coal gas in high-efficiency IGCC systems. These research areas include the following:

1. Combustion Systems:

- (a) To increase confidence in analytical predictions of combustion in gas turbine combustors, bench-mark experimental data for LBtu gas applications are needed. These include measurements of temperature and concentrations in turbulent CO/H₂/CH₄ flames with varying amounts of inerts. The experiments will also provide quantitative data on flame ignition and extinction.
- (b) Only marginally acceptable levels of fuel nitric oxide (NO_x) can be removed from the stack gas by selective catalytic reactor (SCR). Demands on the SCR can be reduced drastically if the nitrogen reactions are controlled by 2-stage (rich-lean) combustion.

Existing model/computer codes are well suited for predicting conversion of fuel nitrogen to nitric oxide (or N₂) during combustion of LBtu gas in industrial gas turbines. However, in-situ measurements are needed to validate and to increase confidence in model predictions.

2. Internal Fluid Mechanics:

The gas turbine efficiency can be increased by streamlining the compressed air flow to minimize pressure losses in the compressor/combustor wrapper, especially in the dump diffuser region. The gas turbine laboratory, currently being developed at Clemson University, will provide a unique facility to study internal fluid mechanics in sections between the compressor discharge and the gas turbine blades.

3. External Systems:

The air-extraction manifold and control valves must be designed and optimized to minimize pressure losses.

4. Transient Response of Subsystems:

Operation of subsystems, such as the booster pump, compressor and control valves between air extraction and booster pump inlets, must be evaluated during plant transients.

8.0 EFFECT OF MANHOLE AIR EXTRACTION ON THE GE MS-7001F SERIES GAS TURBINES

To predict the effect of manhole air extraction in a GE MS-7001F gas turbine for an IGCC application, a computational analysis was conducted. The analysis explains how air extraction through manholes affects the distribution of air flow around the transition pieces. In this analysis, the flow field was numerically solved for a 2-dimensional domain, and the κ -1 model was used in the computational procedure. The results indicate that the flow of air impinging on the inner sleeve of the transition pieces is not uniformly distributed even when air is not extracted through the manholes: the ratio of the difference between the largest and the smallest of the mass fluxes through the holes to the average mass flux is about 1.34. In the presence of extraction, the distribution of impingement air becomes even more nonuniform. Some of the holes experienced reverse flow, a process in which air comes out of the impingement holes. When air is extracted through 2 manholes, the difference between the maximum and the minimum of the mass fluxes is about 6.83 times the average. However, when 14 manholes are used for extraction, the distribution of the flow of impingement air becomes more uniform and the ratio is around 3.06. It is concluded that manhole air extraction causes a high degree of nonuniformity of the impingement flow rates around the transition pieces. As a result, this nonuniformity can significantly undermine the cooling requirement of the transition pieces.

9.0 AIR EXTRACTION FROM THE COMPRESSOR DISCHARGE: EXPERIMENTS AND ANALYSIS

In the first phase of this contracted research, a comprehensive investigation was performed. Principally, the effort was directed to identify the technical barriers which might exist in integrating the air-blown coal gasification process with a hot gas cleanup scheme and the state-of-the-art, U.S. made, heavy-frame gas turbine. The guiding rule of the integration is to keep the compressor and the expander unchanged if possible. It is understood that the technical barriers exist because the advanced gas turbine and IGCC technologies are new technologies at their onset. As a result, we face a number of challenges that we expect will be overcome by the joint effort of government, industry, and university. Because of the low-heat content of coal gas from the air-blown gasification process, the combustor and perhaps the flow region between the compressor exit and the expander inlet might need to be modified to accommodate air extraction required by the thermodynamic cycle. The flow region would include the compressor/combustor prediffuser (also referred to as the prediffuser) and the dump diffuser.

From a structural consideration, air extraction at manholes of the engine wrapper would lead to the simplest design. Our concern was the adverse effects of air extraction on the impingement cooling of the transition pieces. An approximated analysis substantiated that speculation. The research group at Clemson University suggested using a Griffith diffuser for the prediffuser and extracting air from the prediffuser inlet.

In the second phase of the contract, the research established that the analytically identified problems in the impingement cooling flow and the redistribution of the air around the combustor are factual. This phase of the contract substantiated experimentally the advantage of using the Griffith diffuser with air extraction at the diffuser inlet.

A gas turbine test facility housed in a 1500-ft.² building was developed as a part of this experimental program. A 35% scale test model of a heavy-frame gas turbine was constructed and instrumented for this research. The model is a 360-degree representation of the gas turbine instead of a circumferential segmental model. Because of the presence of side walls, particularly in areas where flow had an adverse pressure gradient, a segmental test section could induce local flow separation causing the flow field of interest to undergo significant modification. Three extraction manifolds were designed, fabricated, and tested to establish a near optimum design with the least pressure loss in achieving air extraction. The experimental facility also includes instruments and accessories for automated pressure and velocity measurements.

The through flow was provided by an industrial fan rated 15,000 CFM at 40" H₂O head. The air extraction was provided by a 2-stage centrifugal blower rated 3,500 CFM at 5 psid. The

prediffuser inlet Reynolds number for the scale model was 1×10^5 , while the corresponding Reynolds number for the prototype was 2.5×10^6 . The flow in both the model and prototype are characterized as fully turbulent. Therefore, even though there is more than one order of magnitude difference between those two Reynolds numbers, the basic features of the flow in the model would remain representative for the prototype. Quantitatively, the model might exhibit a slightly higher percentage of total pressure loss than what would take place in the prototype.

The experiments were conducted with the straight wall prediffuser and the modified diffuser referred to as the Griffith diffuser. Both prediffuser designs were tested with and without air extraction. When the straight wall prediffuser was used, the air was extracted at the turbine wrapper. When the Griffith diffuser was used, the air was extracted at the prediffuser inlet.

Four tests with an extraction of 0%, 20%, 12%, and 6% of the through flow were considered at 8000 CFM or the full load. Twenty percent air extraction (1,600 CFM) is referred to as the full extraction. Tests were also conducted at partial load, when the flow through the test section was 60% of that in the full load operation (5,000 CFM). At partial load, 3 tests with an extraction of 0%, 20% and 12% of the through flow were considered. Thus, a set of 7 tests were conducted for each of the two prediffuser designs resulting in a total of 14 tests. While the pressure throughout the test model was measured for all 14 test runs, the detailed profiles for each of the two prediffuser designs were obtained only at full load with no extraction and with full extraction.

These test runs were intended to provide data for the following issues:

- (1) The total pressure losses in the prediffuser and dump diffuser
- (2) The airflow distribution around the combustors and transition pieces
- (3) The sink effect of the combustor bypass holes on the flow field in the prediffuser and the dump diffuser
- (4) The pressure drop in the air extraction path, including the manifold and collection branches

The pressure was measured in the test model and flow systems at more than 300 locations. Measurements for flow mapping included static pressure, total pressure and velocity profiles at 11 stations. Hot-film, Kiel tube, and pitot-static probes were used at 10 stations. For the eleventh station, where a physical probe could not reach, a 2-component LDV system was used. The profiles were measured only at planes of symmetry where the flow was 2-D.

Because of the complexity of the flow field, even with such extensive measurements, the measurements were inadequate to construct a comprehensive description of the entire flow field. Therefore, a closely approximated 3-D computational fluid dynamic analysis, using the commercial code PHOENICS, was performed to supplement the flow description. This type of analysis is costly, but it was felt that the information obtained warranted the effort. The computed velocity profiles agreed well with the measured profile in the flow region where the flow was essentially 2-D. In flow regions where the measured flow field might be sufficiently affected 3-dimensionally, the correlation between computers and measured velocities remain reasonable considering the possible misalignment of the support struts in the test model. Therefore, we believe it is acceptable to present the findings of this research based on the combination of computational/experimental observations. The following are the key features of the flows:

- * In all the test runs, 3 recirculating regions were observed. One of those is a large recirculating region that exists underneath the impingement sleeve near the turbine expander inlet. The other two recirculating regions are small. One exists at the tip of the prediffuser's outer wall, and the other exists in the space between the combustor casing and the prediffuser's outer wall. All recirculation flows dissipate energy and therefore are the sources of loss.
- * In all the tested runs, the bypass holes exerted a strong influence on the prediffuser flow and caused the flow to accelerate locally at the prediffuser exit near the outer wall. This phenomenon is referred to as the sink effect, which causes flow at the prediffuser exit to make a 180-degree turn and short circuit most of the dump diffuser. Thus, the sink effect makes the dump diffuser ineffective, resulting in a high loss of total pressure there.
- * The anticipated flow redistributions around the transition pieces and the combustors were substantiated. Evidence from the lampblack flow visualization shows that a certain portion of the transition pieces received no cooling flow, and computed results show that cooling flow would exit from the impingement cooling holes into the dump diffuser if the air extraction is applied at the manholes. Furthermore, the nonuniformity of the flow around the combustor could mean hot spots on the combustor liner or a deterioration of the temperature-pattern factor.
- * Extraction at the prediffuser inlet, using the Griffith diffuser, would not result in the adverse flow scenario of inadequate cooling of transition pieces. The total power loss in the pre- and dump diffusers for a Griffith diffuser extraction scheme is nearly half of that in the manhole extraction scheme.
- * The total pressure loss in the air extraction path, including the manifold and collection branches, was near optimum situation. Based on a loss breakdown analysis, the

measured entrance loss of the collection branches seems too high. Further improvements should be possible. As is, the observed loss for air extraction is acceptable.

Finally, we believe that the prediffuser for heavy-frame gas turbines can be redesigned to reduce the total pressure loss. In general, the area ratio of the prediffuser should be increased to the extent that the flow would not separate. The length of the prediffuser should be reduced to minimize the area of the "wetted surface." Certain portions of the dump diffuser could be blocked off to reduce the region of the major recirculating flow. The precise area ratio and length of the optimized prediffuser and the location(s) where the dump diffuser will be blocked off will have to be determined for individual cases. In summary, the impact of a proper scheme for air extraction and the redesign of the prediffuser are significant and may cause the overall thermal efficiency to increase by one percentage point in an IGCC power plant.

10.0 REFERENCES

Beebe, K.W., and Blanton, J.C., 1985, "Design and Development Test of a Heavy-Duty Industrial Gas Turbine Combustion System for LBtu Coal Gas Fuel," ASME Paper 85-GT-45.

Blanton, J.C., and Smith, D.P., 1985, "Gas Turbine Combustion of a Minimally Cleaned, Coal-Derived LBtu Gas," ASME Paper 85-GT-160.

Lawson, C.C., 1985, "Water-Cooled Components Testing Program," DOE/MC/20192-1953, NTIS Order No. DE86006598.

Yang, Tah-teh, Agrawal, A.K., and Sheu, M-J., 1990, "LBtu Combustion Model Evaluation," Topical Report to GE Corporate Research & Development under DOE Contract, DE-AC21-86MC23168, Department of Mechanical Engineering, Clemson University.

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