THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
345 E. 47th St., New York, N.Y. 10017

96-GT-290

EVALUATION OF THERMOCHEMICAL RECUPERATION AND PARTIAL OXIDATION CONCEPTS FOR NATURAL GAS-FIRED ADVANCED TURBINE SYSTEMS

Joseph K. Rabovitser
(312) 890-6455

Mark J. Khinkis
(312) 890-6445

Institute of Gas Technology
Des Plaines, IL

Ronald L. Bannister
(407) 281-3270

Frank Q. Miao
(407) 281-3228

Westinghouse Electric Corporation
Power Generation Business Unit
Orlando, FL

BREAK

ABSTRACT

An investigation into the potential benefits of thermochemical recuperation and partial oxidation in advanced natural gas-fired turbine systems is being carried out by a team consisting of the Westinghouse Electric Corporation and the Institute of Gas Technology under contract to the U.S. Department of Energy and the Gas Research Institute. The purpose of this study is to determine whether the application of thermochemical recuperation and/or partial oxidation technologies to advanced natural gas-fired power generation systems provides performance and/or cost benefits. This paper presents an overview of the concepts and technologies which are under investigation, as well as several of the thermodynamic cycles which are being developed to determine their viability.

INTRODUCTION

Natural gas-fired advanced turbine systems (GFATS) studies conducted by the Westinghouse Electric Corporation in support of the U.S. Department of Energy's Advanced Turbine Systems (ATS) Program found that to meet cycle thermal efficiencies greater than 60%, on a lower heating value (LHV), both cycle innovations and gas turbine design improvements, including raising the turbine inlet temperature, are required (Little et al., 1993; Bannister et al., 1993). Cycle innovations have a good potential to significantly increase GFATS effectiveness (Briesch et al., 1995).

As a result of the ATS cycle studies, it was suggested by Westinghouse that for the development of the next generation GFATS using advanced cycle concepts with a higher degree of technology risk, concepts such as thermochemical recuperation (TCR), and/or partial oxidation (PO) combined with flue gas recirculation (FGR), and air and fuel preheating be considered for further study. In collaboration with the U.S. Department of Energy and the Gas Research Institute (GRI) these advanced thermodynamic cycle concepts are being investigated by a team consisting of Westinghouse and the Institute of Gas Technology.

Thermochemical recuperation uses the ability of changing the quality of fuel energy for reducing the irreversible losses of the work equivalent (fuel's capacity for work) during its combustion in heat engines. Thermochemical recuperation in GFATS utilizes heat in the turbine exhaust for preheating a mixture of natural gas and oxygen carrier which reforms the natural gas into H_2 and CO, and thereby returns a significant portion of exhaust heat back to the high temperature part of the cycle. Natural gas reforming can be performed with different oxygen carriers such as steam, carbon dioxide, flue gases and their combination. The primary advantages of TCR is more effective recuperation (two to three times) than conventional recuperation, and the possibility to produce low-Btu H_2-enhanced fuel for improving the performance, including emissions, of the combustion process.

In spite of the potential for TCR to improve thermal energy utilization, system efficiency, and emission reduction, its application in the power generation industry has not been widely accepted, because some significant technical challenges have yet to be overcome. Some of these challenges include: kinetics, heat transfer rates, temperature approach to equilibria, catalysts, materials, as well as capital and operating costs.

Partial oxidation allows the use of fuel energy in two or more stages that provides a possible potential for cycle optimization. In

Presented at the International Gas Turbine and Aeroengine Congress & Exhibition
Birmingham, UK — June 10-13, 1996

PO systems at least one gas turbine operates on the products of partial oxidation (autoreforming or gasification) of natural gas. The primary advantage for PO cycles are operation with low excess air levels and low air compressor work, ultra-low NO_x for PO stages, and less cooling for the same gas turbine inlet temperature (fewer losses).

The joining of TCR and PO combines the advantages of both concepts. There are some synergistic merits (especially for reforming with recirculated flue gases) such as lower temperature for fuel reforming, less need for oxygen carriers, more flexibility for different applications, and combustion of low-Btu reformed fuel with ultra-low excess air, that results in high efficiency and low emissions. This paper reflects the first step in a study of TCR and/or PO applications for GFATS, and focuses on gas turbine cycle configurations wherein the TCR/PO advantages are greatest. The utilization of the TCR and/or PO concepts into combined cycles provides redistribution of the energy utilized in the topping and bottoming cycles due to recuperation and/or staging in the topping cycle. Therefore, the TCR/PO cycle analysis is convenient to conduct using the effect of the energy distribution on total system efficiency.

BACKGROUND

The most extensive research and development work on utilization of the TCR and PO technologies was performed within the former USSR since the 1960s. One of the primary documents, which addresses TCR, is a treatise "Energy of the Fuel" published by Nosach (1989). The TCR concept was initiated in the 1970s for magnetohydrodynamic systems, and then expanded for all heat engines, including gas turbines, internal combustion engines, and industrial furnaces. Their work concentrated on CO_2/H_2O fuel reforming and on utilizing flue gases for fuel reforming.

There has been some related efforts in the U.S. One of these involved the work done by the California Energy Commission (CEC) on TCR for gas turbines (Janes et al., 1990). In CEC's study, the conceptual plant used the most advanced aeroderivative gas generator available which incorporated intercooling between low and high pressure compression steps. A reheat combustor raised the temperature of the gas generator flow before its expansion through a large power turbine of a new steam-cooled design. High grade energy remaining in the power turbine exhaust was recovered by means of the partial methane steam reformer and recycled as an ultra-clean burning hydrogen-rich fuel gas.

The Institute of Gas Technology (IGT) has stressed the importance of this technique for efficient heat recovery in high-temperature advanced gas turbines, as well as internal combustion engines. At the Workshop to Define Gas Turbine Research Needs (1991), held at the South Carolina Energy Research and Development Center, IGT presented information on TCR and suggested that a simple TCR system can increase efficiency by 2 to 4% points. Whereas, a more advanced system might add 10 to 15% points. There has been gas turbine cycle analysis performed by Fluor Daniel, Inc. for GRI, (Bautista et al., 1993), however, only two TCR cycles, aeroderivative chemically recuperated gas turbine cycle and aeroderivative intercooled chemically recuperated gas turbine cycle, were analyzed. The analysis of TCR by Fluor Daniel was performed using steam and methane, and only at a relatively high pressure. Fluor Daniel recognized that more extensive TCR work should be conducted. A conclusion by Fluor Daniel was that an intercooled chemically recuperated cycle showed the lowest cost of electricity over the entire capacity factor range in the 115 MW to 200 MW gas turbine size category.

Other organizations in the U.S. which have performed work on TCR include Pacific Gas and Electric Co., Princeton University, University of California (Kesser et al., 1994), General Electric, Foster Wheeler, and Energy Storage and Power Consultants. Unfortunately, all studies except the fundamental study done by Nosach, 1989, utilized only steam for reforming and did not consider recuperation by air preheat, and some other advanced techniques for system optimization and efficiency increase.

An analysis of a gas turbine cycle utilizing TCR and four stages of PO has been performed at Dartmouth College, and University of Aachen. Harvey et al., 1995, published work on utilizing recycled exhaust off-gases and mixing the gases with methane prior to injection into a reformer. This cycle featured utilization of closed-loop steam condensation and water injection in the recuperation system. The composition of the gas utilized as an oxygen carrier is 1 mole CO_2, 5.25 moles H_2O, and 7.52 moles N_2 per one mole of CH_4. Since the CO_2/H_2O mole ratio is 1:5.25 in the referenced cycle, instead of 1:2 as in the real flue gases, the reforming process should be considered as steam/methane reforming. The heat required for the endothermic reforming reactions is provided by the gas turbine exhaust gases. Assuming state-of-the-art technology, an overall cycle efficiency of about 65% (LHV) can be attained.

The concept of PO for use with gas turbines is not new. It was studied by the Institute of High Temperature (IVTAN) since the late 1950s. Christianovich et al. (1976) published a paper describing a method for the multi-stage combustion of high-sulfur residual fuel oil in a thermal power station at commercial scale. In the paper, he reports that in the first stage of combustion, high-pressure steam and fuel gas are produced. The latter is cooled and freed of ash and sulfur compounds. The steam and the purified gas are then used for power generation. The method gives a high rate of sulfur removal and considerable reduction of nitrogen oxide emission. This new power station concept employs gas turbines and steam/gas turbines to achieve the optimal use of energy.

Jacques Ribesse of the JARIX company in Brussels, Belgium, is involved in new technical developments which include PO gas turbines and high temperature heat exchangers (Ribesse, 1991). Ribesse originally patented the PO gas turbine in 1970, but patented further improvements in 1991. His patent discusses the gas turbine and includes an air compressor, a hydrocarbon catalytic partial oxidation reactor, and an expansion turbine. Partial or total combustion of the combustible gas moving through the expansion turbine is brought about by injecting air into the vanes, while simultaneously ensuring both their cooling and an isothermal expansion. Conversion of the traditional gas turbines into oxidation turbines is, therefore, possible. The upgrading of the thermal waste in the turbine enables heat cogeneration at high temperature to take place.

An innovative combined cycle utilizing a PO gas turbine has been developed at IVTAN which can be retrofitted for repowering existing natural gas-fired steam turbine power generation plants (Maslennikov et al., 1992). The retrofit modifications can result in incremental fuel efficiencies of between 70-80%, and a reduction of total NO_x emissions by more than a factor of 10.

TWO-CYCLE GAS TURBINE SYSTEM

In general, a two-cycle gas turbine power system consists of a topping cycle(s), a recuperation system, and a bottoming cycle as shown in Figure 1. Total energy input in the system (Q_T) is distributed between topping (Q_{top}) and bottoming (Q_{bot}) cycles, where $Q_T = Q_{top} + Q_{bot}$. Energy in the topping cycle exhaust is equal to $Q_{exh} = Q_T - Q_{top}$. The recuperation system is placed between the topping and bottoming cycles. The energy input in the bottoming cycle is defined as $Q_{bot} = Q_{exh} - Q_R$. If the thermal efficiencies of the topping and the bottoming cycles are different, the total system efficiency strongly depends on how the total energy input is distributed between the topping and bottoming cycles. In combined cycles, the bottoming cycle is a steam turbine cycle. A preliminary study of GFATS shows that the main potential for improvement in total system efficiency is in the increase of the portion of the energy utilized in the topping cycle (Y_{top}), i.e., decrease of energy portion utilized in the bottoming cycle (Y_{bot}). Most of the cycle innovations (air and fuel preheating, TCR, reheat, partial oxidation, etc.) increase Y_{top}. Modifications, such as an improvement in the turbine cooling system, also increases Y_{top} and decreases Y_{bot}.

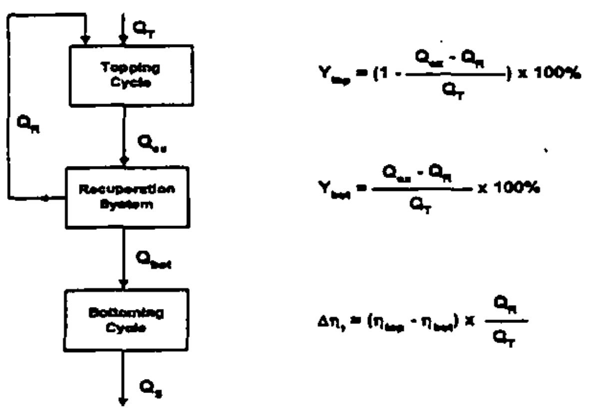

Figure 1. Two-Cycle Gas Turbine System

The two-cycle gas turbine power system analysis is more convenient to conduct using the relationship between total combined cycle efficiency (Eff-cc) and the portions of energy utilized in the topping and bottoming cycles. It is easy to show that Eff-cc can be defined as Eff-cc = Eff-top x Y_{top} + Eff-bot x Y_{bot}, where Eff-top and Eff-bot are efficiency of the topping and bottoming cycles. These efficiencies are ratios of power output (W_{top} and W_{bot}) to energy utilized (Q_{top} and Q_{bot}) in the cycles, Eff-top = W_{top}/Q_{top} and Eff-bot = W_{bot}/Q_{bot}.

To illustrate the effect of energy distribution between topping and bottoming cycles on total combined cycle efficiency, the relationship between Eff - cc and Y_{top} for various bottoming cycle efficiencies is presented in Figure 2. A topping cycle efficiency of 98% was selected. (Combined mechanical, heat and electrical losses are estimated to be about 2%.) The bottoming cycle efficiency (Eff - bot) includes stack losses (L_{stack}). The relationship between bottoming cycle and steam turbine cycle (Eff-st) efficiencies is Eff-bot = Eff-st X (1 - L_{stack}/Y_{bot}).

If Y_{top} is equal to 35% (Y_{bot}= 65%) and the topping cycle efficiency is equal to 98%, then the bottoming cycle efficiency should be more than 40% (Eff-bot > 40% and Eff-st > 43%) to achieve total cycle efficiency greater than 60% (Figure 2). If Y_{top} can be increased to 40% (Y_{bot}= 60%), for instance by improving the turbine cooling system, then the combined cycle efficiency will be about 63% at the same topping and bottoming cycle efficiencies (Figure 2).

It is important to note that the total combined cycle efficiency, in the range of 60 to 63%, is the maximum magnitudes that can be achieved utilizing simple combined cycle configuration with Y_{top} in the range 35-40% (Y_{bot}= 60-65%). Greater efficiency may be obtained utilizing advanced combined cycle configurations with TCR and/or PO.

The recuperation system returns a portion of energy input into the bottoming cycle back to the high temperature topping cycle that reduces Y_{bot} and increases Y_{top}. A percentage point of increase of recirculation energy decreases Y_{bot} and gives an increment of total cycle efficiency in the range of 0.5 to 0.8 percentage points (Figure 2). TCR is significantly more effective than conventional recuperation. The comparison between TCR and conventional recuperation shows that the heat recovered can be about two times more in the same temperatures range at a natural gas reforming rate of only 50%.

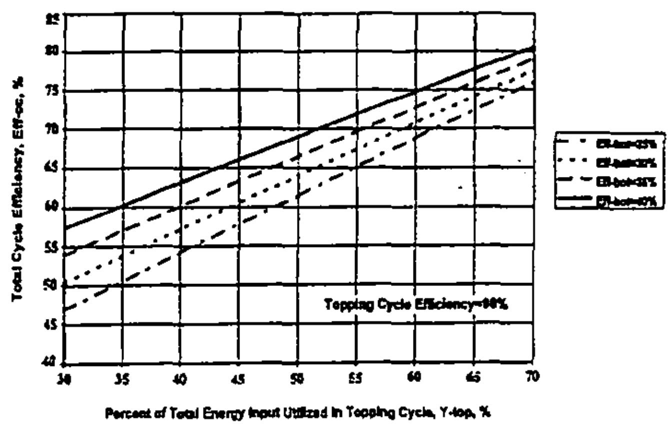

Figure 2. Effect of The Percent of Total Energy Input Utilized in Topping Cycle on Total Cycle Efficiency

Partial oxidation reduces total excess air that decreases gas turbine exhaust flow and Y_{bot} (at the same gas turbine exhaust temperature). For instance, a 10% reduction in total excess air reduces Y_{bot} by about 3% and gives an increment of Eff-cc in the range of 1.5 to 2.4 percentage points.

Preliminary estimate of GFATS with TCR and PO shows that incorporation of TCR and PO increases Y_{top} at least to 50% and combined cycle efficiency up to 64 to 69% for different bottoming cycle configurations.

ADVANCED CYCLES UTILIZING THERMOCHEMICAL RECUPERATION

As discussed, TCR gas turbine cycles utilizing natural gas/steam reforming have been studied by California Energy Commission, Fluor Daniel, University of California, etc. The Westinghouse/IGT study concentrates on TCR with flue gas recirculation (FGR) and a combination of steam and FGR. A TCR/FGR gas turbine topping cycle is shown in Figure 3. This cycle configuration is based on principles for TCR power systems developed by Nosach, (1989).

In the TCR/FGR cycle, Figure 3, a portion of exhaust flue gases is withdrawn from the bottoming cycle, cooled, compressed in an additional flue gas compressor, mixed with natural gas and enters the heat recovery reformer. In this reformer, the natural gas/FGR mixture is heated and reformed utilizing the gas turbine exhaust heat. Reformed fuel, at an exit from the heat recovery reformer, enters the combustor. Natural gas-reforming is an endothermic reaction, therefore, the natural gas/FGR mixture absorbs heat thermally (as it is heated) and chemically (via fuel reforming), resulting in a larger recuperation of turbine exhaust energy compared to conventional recuperation, for instance, air or FGR preheating.

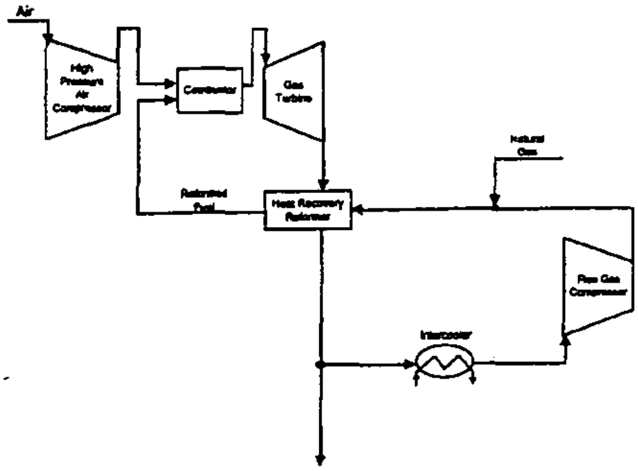

Figure 3. Gas Turbine Topping Cycle with Thermochemical Recuperation

The natural gas-reforming rate (and the exhaust heat recovered) can be increased by low oxygen content in the reacting mixture, low pressure, high temperature, and a high ratio of FGR to natural gas. Therefore, in order to take full advantage of the TCR concept, the gas turbine combustor is operated at near stoichiometric air-to-fuel ratio (not more that 10% of excess air at the combustor exit) and the FGR is used to quench the combustion products down to a desired turbine inlet temperature. This minimizes the air flow and oxygen content in the exhaust flue gas. Both the air compressor flow rate and stack exhaust flow rate will be less than half that of conventional cycles with the same turbine size.

Another merit of TCR, as a cycle innovation for GFATS, is low emission combustion of reformed fuel. This technology is based on efficient combustion of low-Btu H_2-enhanced fuel. Three major techniques are utilized to achieve low emissions for both NO_x and CO. The first technique is natural gas-reforming for H_2 and CO production. The second technique is utilization of FGR as an oxygen carrier for natural gas reforming and as a diluent to obtain a low-Btu fuel. The third technique is combustion with low excess air. For example, natural gas/FGR reforming at 620°C (1150°F), 20 bars (295 psi), and a recycling coefficient of 1.2 produces a low-Btu reformed fuel containing 14.2% combustible gases (8.4% H_2, 2.4% CO, and 3.4% CH_4), and its LHV is only 2280 kJ/m^3 (61.2 Btu/SCF). According to IGT's experimental data for this type of low-Btu fuel, combustion (diffusion flame) with low excess air produces a total NO_x level of less than 8 vppm (at 3% O_2).

Thus, it can be stated that TCR as a cycle innovation has advantages for both efficiency and emissions. Combustion of reformed fuel returns the use of diffusion flame (in opposite to premixed flame) for ultra-low NO_x combustors with advantages in flame stability, high turndown ratio, startup conditions, etc.

The TCR cycle in Figure 3 is only one of several possible TCR cycle configurations. Identification and parametric optimization of the best TCR cycles are major goals to be completed within the current study. Application of TCR for GFATS requires development of a heat recovery reformer, flue gas compressor, and combustor modification. The gas turbine can be directly used because the combustion product composition is similar to conventional gas turbine systems. Development of required specifications for a heat recovery reformer, flue gas compressor and a modified combustor are to be completed during this study.

PARTIAL OXIDATION GAS TURBINES

The other major concept being studied by the Westinghouse-led team is PO. Conventional power systems utilizing gas turbines are designed for operating on products of complete combustion of fuel. As mentioned, in the PO technology at least one gas turbine operates on products of partial oxidation (autoreforming or gasification) of the fuel.

The main differences between a PO gas turbine (some call it reverse reheat) and the classical gas turbine are: 1) reduced compression air flow of about 65%, for the same expansion turbine, 2) larger volumetric gas flow in the turbine (15-20%), taking into account the lower specific mass of the partial oxidation products, and 3) close to isothermal expansion, allowing a better utilization potential of the heat. A comparison of reheat and the PO shows that for a reheat system, there is 100% air and a portion of fuel injected in the first combustor and only fuel is injected in the second combustor. For PO, 100% fuel and a portion of the air is injected in the first combustor and only air is injected in the second combustor. Excess air in the first combustor serves to cool the reaction somewhat before combustion is completed in the second combustor for the reheat case, while PO occurs in a substoichiometric atmosphere at a lower temperature.

A PO topping cycle is shown in Figure 4. For a 100% fuel flow and a substoichiometric high pressure, compressed air flow enters the partial oxidation reactor. The partially oxidized combustion products feed the PO gas turbine. The products from the PO gas turbine exit at a reduced pressure and enter the low pressure combustor as a low-Btu H_2-enhanced fuel. A low pressure compressed air also enters the low pressure combustor for complete combustion and quenching the combustion products down to a required turbine inlet temperature. Exiting from the low pressure combustor are conventional combustion products that are fed into a conventional low pressure gas turbine, as shown in Figure 4. The level of substoichiometric air-to-fuel ratio for the PO stage is selected to establish the desired inlet temperature for the PO gas turbine. The air-to-fuel ratio for the system is near stoichiometric (less than 10% excess air at the low pressure combustor exit). Operation at low excess air provides an increase in Y_{top} and a decease in Y_{bot}, and, as a result, a significant increase in combined cycle efficiency.

In the first-stage of the cycle, Figure 4, the partial oxidation occurs in a reducing atmosphere at a lower temperature which almost eliminates NO_x formation. In the second stage, a low-Btu H_2-enhanced fuel is combusted at a very low level of excess air, and at these conditions NO_x and CO emissions are much lower than those for a conventional gas turbine.

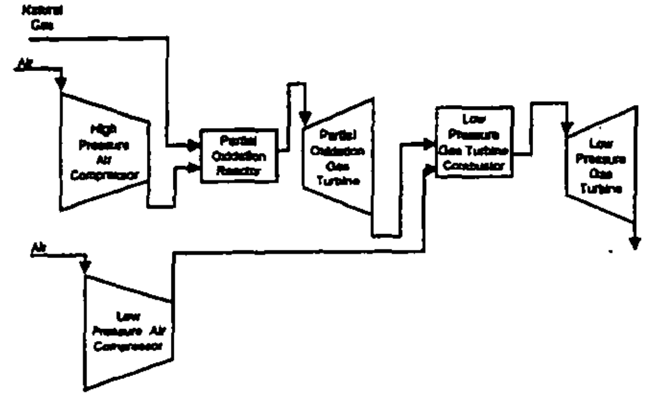

Figure 4. Gas Turbine Topping Cycle with Partial Oxidation

Partial oxidation can be used for a combined cycle, greenfield application. Also a PO gas turbine can be effectively utilized for repowering. IVTAN proposed to utilize the one-stage PO topping cycle as an addition to existing gas- or oil-fired steam turbine units (Maslennikov et al., 1992). A PO combined cycle, which reflects IVTAN's repowering concept, is shown in Figure 5. The topping cycle is a one-stage PO cycle comprised of an air compressor, partial oxidation reactor and PO gas turbine. Steam is added to the partial oxidation reactor to provide PO at very low substoichiometric conditions and for suppressing of soot formation. The PO gas turbine exhaust includes a significant portion of H_2 and CO that is fed as a gaseous fuel to the boiler burners. Combustion air is supplied by a separate blower. The bottoming cycle is a conventional steam turbine cycle with a fuel-fired boiler, steam turbine, condenser, regeneration system, feed water and condensate pumps, etc. IVTAN's calculations show that for PO combined cycles, the efficiency of additional electricity production can achieve more than 75%.

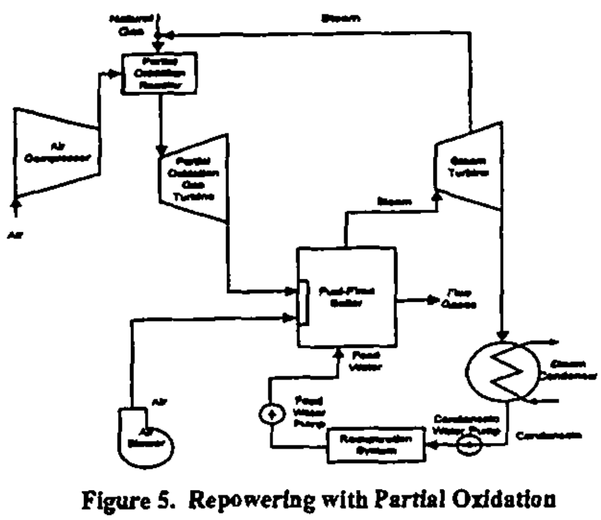

Figure 5. Repowering with Partial Oxidation

Applications of PO for GFATS requires development of a PO gas turbine, partial oxidation reactor and low pressure combustor modification. Specifications for this equipment will be developed within the current study.

NATURAL GAS-FIRED ADVANCED TURBINE SYSTEMS

Repowering of aged power plants is a good opportunity for utilization of GFATS. The area of repowering application can be significantly extended, especially for coal-fired steam turbine power systems, when TCR and/or PO are used in the GFATS. For repowered coal-fired power systems it is important to keep in operation, at full capacity, the existing coal combustion system (combustion air supply, and coal supply and preparation systems) without modifications. This will provide high cost effectiveness for repowering.

A repowering system for coal-fired power systems utilizing GFATS with TCR and/or PO is shown in Figure 6. The existing coal-fired power systems is a conventional coal-fired steam turbine unit, and the GFATS serves as a topping cycle. The GFATS exhaust enters the coal-fired boiler. This exhaust could be either reformed fuel (as shown in Figure 6) or inert products of complete combustion. When the exhaust is a reformed fuel, this system can also be used for the reburning in coal-fired boilers as an effective NO_x reduction technology.

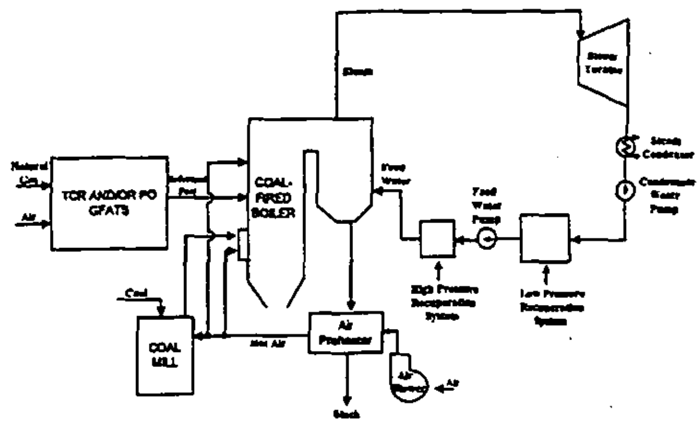

Figure 6. Repowering of a Coal-Fired Steam Turbine Plant Utilizing Natural Gas-Fired Advanced Turbine Systems with Thermochemical Chemical Recuperation and/or Partial Oxidation

As mentioned, one of the advantages of the TCR and/or PO systems is operation at low levels of excess air that provides significantly lower exhaust flow rate for TCR/PO systems compared to conventional gas turbine systems. This feature can be efficiently utilized for repowering compared , for instance, with hot windbox repowering. Comparison of three repowering systems with conventional GFATS, GFATS with TCR and with PO is shown in Figure 7, where V_1 and V_2 are GFATS exhaust and combustion air flow rates, respectively, and W_{gt} and W_{st} are power outputs from the gas and steam turbine, respectively. For example, at $V_1/V_2 = 0.25$, the power output increase will be about 30% for conventional GFATS, about 78% for GFATS with TCR, and about 96% for GFATS with PO (Figure 7). For these cases, the total repowered power station efficiency may achieve, respectively, 41%, 48% and 50% at a baseline efficiency of 38% (see Figure 8). Thus, utilization of GFATS with TCR and/or PO should increase both power output and efficiency of the repowered plant, and also reduce NO_x emissions.

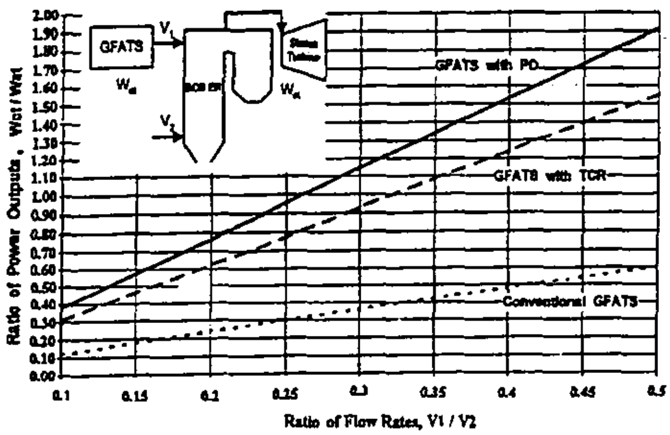

Figure 7. Relationship Between Power Outputs and Flow Rates for Repowering with Conventional, Thermochemical Recuperation, and Partial Oxidation Natural Gas-Fired Advanced Turbine Systems

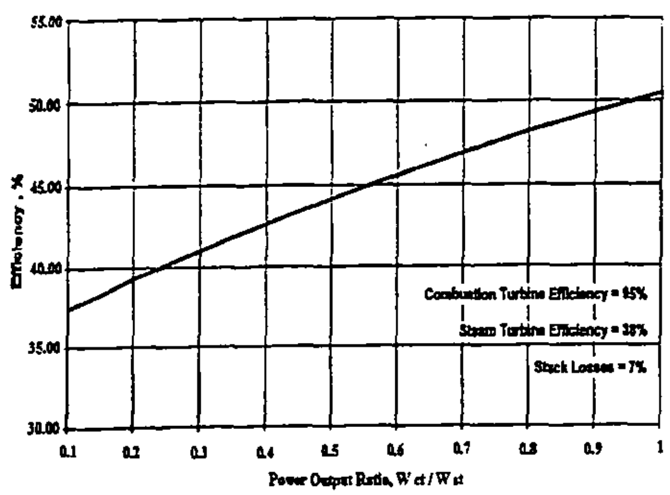

Figure 8. Effect of Power Output Ratio on Repowered Power Station Efficiency

CONCLUSIONS

The next generation of GFATS with system efficiencies up to 68% (LHV) for greenfield power plants and more than 50% (LHV) for repowered coal-fired power plants may be achieved by utilizing such innovative cycle concepts as TCR and PO. Environmentally superior systems that will not require use of post-combustion emissions controls and ensure NOx less than 6 vppm (at 15% O_2) may be developed based on combustion of low-Btu reformed fuel. The current study will define the best cycle configurations for greenfield and repowering applications, and provide parametric optimization for selected systems. Potential hardware and material concerns will be identified, along with an estimate of cost-of-electricity to operate the plants discussed in this paper.

ACKNOWLEDGMENTS

The TCR and PO concepts for GFATS are being studied under U.S. Department of Energy and Gas Research Institute contracts. The program is administered through the DOE Morgantown Energy Technology Center and the GRI Basic Research Department under the guidance of METC's Program Manager, Dr. Richard Johnson, and GRI's Program Manager, Mr. Kevin Krist, respectively.

REFERENCES

Bannister, R. L., Chenuva, N. S., Little, D. A. and McQuiggan, G., 1995, "Development Requirements for an Advanced Gas Turbine System," ASME JOURNAL OF ENGINEERING FOR GAS TURBINES AND POWER, Vol. 117, pp. 724-733.

Bautista, P., Ashok, R., Sander, M., Sculati, J., Francuz, V.,. and West, E., 1993, "Evaluation of Advanced Gas Turbine Cycles," Final Report, Fluor Daniel Inc.

Briesch, M. S., Bannister, R. L., Diakunchak, I. S. and Huber, D. J., 1995, "A Combined Cycle Designed to Achieve Greater than 60 Percent Efficiency," ASME JOURNAL OF ENGINEERING FOR GAS TURBINES AND POWER, Vol. 117, pp. 734-741.

Christianovich, S. A., Maslennikov, V. M. and Sterenberg, V. L, 1976, "Steam-Gas Power Stations with Multi-Stage Residual-Oil Combustion," Applied Energy, Great Britain, Vol. 2, pp. 175-187.

Harvey, S. P., Knoche, K. F. and Richter, H. J., 1995, "Reduction of Combustion Irreversibility in a Gas Turbine Power Plant Through Off-Gas Recycling," ASME JOURNAL OF ENGINEERING FOR GAS TURBINES AND POWER, Vol. 117, pp. 24-30.

Janes, J., DeAngelis, M. and Deller, N. J., 1990, "Chemically Recuperated Gas Turbine," Staff Report, California Energy Commission.

Kesser, K. F., Hoffman, M. A. and Baughn, J. W., 1994, "Analysis of a Basic Chemically Recuperated Gas Turbine Power Plant," ASME JOURNAL OF ENGINEERING FOR GAS TURBINES AND POWER, Vol. 116, pp. 277-284.

Little, D. A., Bannister, R. L. and Wiant, B. C., 1993, "Development of Advanced Turbine Systems," *ASME Cogen Turbo '93 Proceedings*, IGT I - Vol. 8, pp. 271-280.

Maslennikov, V. M., and Shterenberg, V. J., 1992, "Steam-Gas Units for the Modification of Existing Steam Power Plants," (based on aeroderivative gas turbine engines), IVTAN, Moscow.

Nosach, V.G., 1989, "Energy of Fuel," Kiev, Ukraine, Naykova Dymka.

Ribesse, J. J., 1994, "The Isotherm Partial Oxydation Gas Turbine," European Journal, M, Vol. 36, No 1, pp. 27-32.