Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from the Office of Scientific and Technical Information, 175 Oak Ridge Turnpike, Oak Ridge, TN 37831; prices available at (615) 576-8401.

Available to the public from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161; phone orders accepted at (703) 487-4650.
Advanced Turbine System Program
Phase 2 Cycle Selection

Latovich, Jr., John A. (804-763-2353)
ABB Power Generation, Inc.
5309 Commonwealth Centre Parkway
Midlothian, VA 23112

Abstract

The objectives of the Advanced Turbine System (ATS) Phase 2 Program were to define a commercially attractive ATS cycle and to develop the necessary technologies required to meet the ATS Program goals with this cycle. This program is part of an eight-year Department of Energy, Fossil Energy sponsored ATS Program to make a significant improvement in natural gas-fired power generation plant efficiency while providing an environmentally superior and cost-effective system.

Background

By the year 2000 electric power generation demand is expected to increase domestically and on a worldwide basis. To meet this projected increase in power generation, advanced gas turbines are being developed through a Government/industry partnership. This effort, sponsored by the Department of Energy's (DOE) Advanced Turbine System (ATS) Program, is directed toward meeting the program goals of ultra-high efficiency, environmentally superior, and cost-competitive gas turbine systems for the future.

ABB is one of several gas turbine manufacturers participating in the DOE's Fossil Energy (FE) Conceptual Design and Product Development Phase of the ATS Program. As part of that program, tradeoff studies are conducted by utility engine manufacturers to evaluate and select the most commercially attractive advanced turbine system which meets the ATS Program goals. The results of ABB’s tradeoff studies and Advanced Turbine System selection are discussed in detail.

Nomenclature

GT=Gas Turbine
LHV=Lower Heating Value
NOx=Nitrous Oxide Emissions
CO=Carbon Monoxide Emissions
UHC=Unburned Hydrocarbon Emissions
PPM=Parts Per Million
RAM=Reliability, Availability, and Maintainability
EV=Environmental Combustor
SEV=Sequential Environmental Combustor
HP=High Pressure
LP=Low Pressure

Introduction

The objectives for the DOE’s Advanced Turbine System (ATS) require development and demonstration of an ultra-high efficiency, environmentally friendly, cost effective power generation system by the year 2000. These ATS program objectives are to be met by achieving the following goals:
• Natural gas-firing but fuel flexible for adaptation to biomass and coal derived fuels
• High firing temperatures >1427°C
• High combined cycle efficiency (LHV) >60%
• Low emissions (<10 PPM NOx, <20 PPM CO and UHC)
• Reduced bus-bar costs (10%) than current vintage systems
• Equivalent RAM to today's systems
• Demonstration/commercialization by the year 2000

Cycle Studies

To achieve these goals both innovative cycle and high temperature turbine technologies were evaluated. These included intercooling, recuperation, chemical recuperation, high temperature simple cycles, and numerous water/steam based cycles. These cycles were rejected because of system complexity, unproven components, high operating temperatures, high operation and maintenance costs, excessive water demands, and the physical size of the system and system components.

In lieu of these cycles, the ABB Model GT24 Advanced Cycle System (ACS)™ was selected as the reference plant. The GT24-ACS already incorporates several innovative cycle improvements including a reheat cycle, an annular low-NOx sequential combustion system, and a high pressure ratio compressor which makes the size and cost of plant hardware comparable to smaller size plants. In addition, the GT24-ACS has been able to take advantage of the development and field experience of the ABB Model 13E2 Engine which operates at 50 Hz and shares annular combustor and turbine features with the GT24-ACS.

Figure 1 - ABB Advanced Cycle System (ACS)

The ABB Advanced Cycle System (ACS) is shown in the Temperature versus Entropy graph in Figure 1. The reheat cycle follows a path of 1-2 for compression, 2-3 for combustion in the first combustor (EV), 3-4 for expansion in the HP turbine, 4-5 for combustion in the second combustor (SEV), and 5-6 for expansion in the LP turbine. The simple cycle follows the path of 1-A for compression, A-B for combustion, and B-C for expansion. To achieve the same power output, the simple cycle requires operation at higher firing temperatures to achieve improved cycle efficiency. With the reheat cycle, this power level can be achieved at lower firing temperatures as virtually all of the cooling air used for the EV combustor and HP turbine can be recycled through the SEV combustor and LP turbine cycles for improved efficiency.

The performance characteristics of the GT24-ACS which make it suitable for upgrading to meet ATS program goals include the following:

• Pressure ratio of 30:1 for smaller hardware size, higher specific power, and reduced tip speeds and stresses
- Firing temperature of 1255°C
- Simple cycle efficiency of 37.5% (LHV basis)
- Net combined cycle efficiency of 58% (LHV basis)
- Net power output of 165 MW in simple cycle and 251 MW in combined cycle
- Excellent part load performance and emissions from 60-100% load

**ABB ATS Definition**

To meet the ATS program goals, the combined cycle efficiency level of the GT24-ACS needs to be increased by 2%, the firing temperature increased by 170°C, and NOx emissions reduced to lower single-digit values. Considering the analysis results conducted at ATS temperature levels and GT24-ACS test data, ABB is confident that the ATS program goals can be met with minimal risk by upgrading selected parts of the GT24-ACS. Designating this new, higher efficiency plant as the Model GT24-ATS, this new system would consist of the following components:

**Compressor**

The GT24-ATS will utilize the existing GT24-ACS engine compressor. This compressor consists of 22 stages, 16 LP stages and 6 HP stages. Three variable geometry stages are utilized which allow for mass flow reductions of up to 50% for efficient operation between 60-100% load. The compressor blading utilizes controlled diffusion airfoils (CDA) with low stage loading to maximize efficiency levels and surge margin.

Scale model LP compressor rig tests were completed to verify performance levels. The compressor test rig is shown in Figure 2. Blading aerodynamic and stress levels have also been verified through bench and rig testing. No modifications to the compressor are required for the GT24-ATS.

![Figure 2 - GT24 Compressor Test Rig](image)

**Combustor**

The GT24-ATS combustor will utilize the existing GT24-ACS sequential combustion system with only minor modifications to incorporate ABB's third generation EV combustor technology. The sequential combustion system consists of an annular EV combustor downstream of the HP compressor stages. Thirty (30) EV burners are located in the dome of the combustor as indicated in the general arrangement in Figure 3. These burners reflect ABB's patented EV technology whereby low NOx levels are achieved by aerodynamic control of mixing and flame stabilization. ATS levels of NOx will be achieved by improved mixedness in the EV burners. No changes to the combustor wall cooling system are required. Combustion rig testing at ATS firing temperatures indicated wall temperatures less than 900°C.

The output of the EV combustor discharges through the HP turbine stage into a
mixing area and then into the sequential annular combustor, designated as the SEV combustor. Virtually no NOx is produced while extremely high combustor efficiencies are achieved. Twenty-four (24) air cooled lance-type fuel injectors admit gas to the combustor which ignites without the need for ignitors. Combustion rig testing at ATS firing temperatures also resulted in wall temperatures less than 900°C and emission levels in single-digits. This high level of combustion system performance is achieved without the use of variable geometry, steam cooling, or any moving parts. Because the combustors are annular, the amount of surface area required to cool is less than required for typical can-annular systems. In addition, crossover tubes are not required. The annular combustors provides a more even temperature profile to the turbine which is highly desirable for RAM considerations at these higher ATS firing temperature levels.

Incorporate turbine cooling advances (turbulators and advanced wall cooling features)

Utilize single crystal blading for the air-cooled rotor blade stages

Integrate thermal barrier coatings (TBC) with turbine cooling advances and single crystal blading to reduce airfoil cooling air needs

Steam cooling of the GT24 turbine vanes

The turbine exhaust temperature is increased further to improve combined cycle performance

Figure 3 - GT24 Sequential Combustion System Arrangement

Turbine

The GT24-ATS will utilize the GT24-ACS turbine with several improvements. The existing GT24-ACS turbine consists of 5 turbine stages, 1 HP stage and 4 LP stages. Advanced aerodynamics (3-D) and cooling technologies are utilized in the turbine blading to keep metal temperatures below design limits. The blading has been tested aerodynamically and performance levels verified. A welded rotor construction has been maintained consistent with other ABB engine models. DS materials, honeycomb seals, and shrouded blades are used in the turbine for high levels of turbine performance. In addition, the turbine exhaust temperature is higher than conventional simple cycle machines for improved combined cycle performance. The first GT24-ACS turbine is shown in Figure 4 during assembly in Richmond, Virginia, for Jersey Central Power and Light's Gilbert Station.

Figure 4 - First GT24 During Assembly

To meet the ATS program goals, the following improvements to the GT24-ACS turbine are required:

- Incorporate turbine cooling advances (turbulators and advanced wall cooling features)
- Utilize single crystal blading for the air-cooled rotor blade stages
- Integrate thermal barrier coatings (TBC) with turbine cooling advances and single crystal blading to reduce airfoil cooling air needs
- Steam cooling of the GT24 turbine vanes
- The turbine exhaust temperature is increased further to improve combined cycle performance

ABB has prepared development programs to achieve these goals. High temperature blading programs include development of high effectiveness turbulators and advanced wall cooling concepts. These items are tested with full
coverage liquid crystals to determine heat transfer rates and to subsequently optimize cooling of components and passages. Similarly, ABB continues with the development of single crystal materials utilizing combinations of casting simulations, casting trials, and heat treatments in a concurrent engineering approach to optimize the casting process for high yields and reduced costs. ABB continues to evaluate TBC coatings on blading to fully integrate coating characteristics with base materials properties to achieve a satisfactory system. Development program plans included TBC coating and base materials testing at the bench test level and in-situ testing in existing ABB gas turbines. Steam cooling of the turbine vanes is not new to ABB and existing advanced cooling technologies will be applied to optimize the design. To meet the combined cycle efficiency goals of ATS, steam cooling of the combustor and turbine blades are not required.

**Performance**

Based on the combustor and turbine improvements identified, the estimated performance of the GT24-ATS system as compared to the GT24-ACS system is indicated below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>GT24-ACS</th>
<th>GT24-ATS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firing Temp</td>
<td>1255°C</td>
<td>1427°C</td>
</tr>
<tr>
<td>Simple Cycle Efficiency</td>
<td>37.5%</td>
<td>&gt;41%</td>
</tr>
<tr>
<td>Combined Cycle Efficiency</td>
<td>58.0%</td>
<td>&gt;61%</td>
</tr>
<tr>
<td>Simple Cycle Power</td>
<td>165 MW</td>
<td>200 MW</td>
</tr>
<tr>
<td>Combined Cycle Power</td>
<td>251 MW</td>
<td>300 MW</td>
</tr>
<tr>
<td>Exhaust Temperature</td>
<td>617°C</td>
<td>677°C</td>
</tr>
<tr>
<td>Exhaust Airflow</td>
<td>373 Kg/Sec</td>
<td>375 Kg/Sec</td>
</tr>
<tr>
<td>NOx</td>
<td>&lt;25 PPM</td>
<td>&lt;9 PPM</td>
</tr>
<tr>
<td>CO</td>
<td>&lt;20 PPM</td>
<td>&lt;20 PPM</td>
</tr>
<tr>
<td>UHC</td>
<td>&lt;20 PPM</td>
<td>&lt;20 PPM</td>
</tr>
</tbody>
</table>

These performance numbers are based on a triple pressure heat recovery steam generator (HRSG) with reheat.

**Commercialization**

From a commercialization standpoint, the ABB GT24-ATS can take advantage of GT24-ACS experience. The first GT24-ACS was sold to Jersey Central Power and Light and delivered to their Gilbert Station in July, 1995, as shown in Figure 5. This first unit has completed first ignition, full speed running, and synchronization. Five outages are scheduled for RAM testing and evaluation purposes. Commercial operation is scheduled to begin in June 1996. These efforts will substantially enhance and minimize the technical risks in meeting ATS program RAM goals with ABB's GT24-ATS.

![Figure 5 - GT24 Delivered to Gilbert Site in July 1995](image)

ABB has not limited introduction of the Advanced Cycle System to 60 Hz machines such as the GT24-ACS. ABB is also introducing a 50 Hz version of the GT24-ACS designated at the Model GT26-ACS. This machine has a combined cycle efficiency in excess of 58% and will provide power levels of 240 MW in simple cycle operation and 345 MW in combined cycle operation. It is planned that the GT24-ATS improvements will be extended to this product line as well. Currently, two GT26-ACS machines have been sold which
will allow for accumulating experience with both ACS and ATS technologies on a worldwide basis.

Conclusions

ABB’s GT24-ATS can meet or exceed the ATS program goals with minimal risk. In summary, the GT24-ATS:

- Uses the existing and tested GT24 compressor
- Requires only minor modifications to the GT24 EV/SEV combustors to meet NOx goals without using
  - Variable geometry
  - Moving parts
  - Steam cooling
- Utilizes improvements to the GT24 turbine for:
  - Turbine cooling advances
  - Single crystal blading in air cooled stages
  - Integration of thermal barrier coatings with single crystal airfoils
  - Advanced steam cooling of GT24 turbine vanes
- Utilizes the rest of the existing GT24 plant since the proposed changes are internal to the gas turbine only.

Since ABB does not require steam cooling of the turbine rotor or rotor blading to meet the ATS combined cycle efficiency goals, the technical risk to the GT24-ATS is reduced which also eliminates problems associated with leakage of steam to and from rotating hardware.

Acknowledgements

This ATS program effort was conducted in a partnership with the U.S. Department of Energy, Fossil Energy Office, Morgantown Energy Technology Center (METC), Morgantown, West Virginia, with the guidance of the METC Contracting Officer’s Technical Representative, Mr. Charles T. Alsup.

The technical content in this paper also includes information provided by Dr. Prith Harasgama of ABB Power Generation, Ltd., and by Mr. Mike Hargrove and Dr. Tom Gibbons of ABB Power Plant Laboratories.