Advanced Turbine Systems Program

Authors:
Wilkes, C.
Mukavetz, D.W.
Knickerbocker, T.K.
Ali, S.A.

Contractor:
Allison Gas Turbine Division
General Motors Corporation
P.O. Box 420
Indianapolis, Indiana 46206

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CONTRACT INFORMATION

Contract Number
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Contractor
Allison Gas Turbine Division
General Motors Corporation
P.O. Box 420
Indianapolis, Indiana 46206
(317) 230-2548

Contractor Project Manager
Colin Wilkes

Principal Investigators
Dale W. Mukavetz
T. K. Knickerbocker
Dr. Sy A. Ali

METC Project Manager
Leland E. Paulson

Period of Performance
July 1986 - October 1993

OBJECTIVES

The objectives of Phase I of the Advanced Turbine Systems (ATS) program are the following:

- efficiency, on a lower heating value (LHV), greater than 60% for utility-scale, natural-gas-fired, combined-cycle systems; LHV efficiency for industrial-scale systems 15% greater than 1991 vintage efficiency
- base-load emissions consistent with the following:
  - no post-combustion emissions control devices
  - 1991 state-of-the-art system efficiencies
- nitrogen oxides (NOx), 10 parts per million by volume dry (ppmvd) at 15% oxygen
- carbon monoxide (CO) and unburned hydrocarbon (UHC), 20 ppmvd
- cost of electricity (COE) 10% below COE of 1991-vintage power generation systems in the same market class and size range, and meeting the same emissions requirements
- amenable to change for use in a coal-based system
- reliability, availability, and maintainability (RAM) comparable to today's advanced power generation systems
BACKGROUND INFORMATION

Phase I of the ATS program was initiated in the spring of 1992 as System Scoping and Feasibility Studies—a contract modiﬁcation to the existing contract noted previously entitled Advanced Coal-Fired Gas Turbine Systems. Period of performance was approximately six months.

PROJECT DESCRIPTION

In accordance with the goals of the DOE program, improvements in the gas turbine are the primary focus of Allison activity during Phase I. To this end Allison conducted a survey of potentially applicable gas turbine cycles and selected the advanced combined cycle as reference system. Extensive analysis of two versions of the advanced combined cycle was performed against the requirement for a 60% thermal efficiency (LHV) utility-sized, natural gas fired system. This analysis resulted in technology requirements for this system. Additional analysis determined emissions potential for the system, established a coal-fueled derivative system and a commercialization plan. This report deals with the technical requirements for a system that meets the thermal efficiency goal.

Choice of Thermodynamic Cycle

Allison initially investigated four basic thermodynamic cycles:

- humid air turbine
- intercooled-recuperated systems
- advanced combined cycle
- chemically recuperated cycle

Our survey and cycle analysis indicated that all had the potential of reaching 60% thermal efficiency. We also concluded that engine hot section technology would be a critical technology regardless of which cycle was chosen. Based on this result Allison chose to concentrate on the advanced combined cycle. This cycle is well known and understood by the utility turbine user community and is therefore likely to be acceptable to users.

Figure 1 shows the thermal efficiency potential of simple Brayton cycles in the usual format with turbine firing temperature and overall pressure ratio as variables. Superimposed on this plot is a line of constant exhaust gas temperature. A temperature of 1100°F represents current state of the art (SOA) in boiler technology (1200°F represents advanced systems) with higher pressure ratio cycles at given firing temperatures reducing exhaust gas temperature to the bottoming cycle.

This figure yields the following conclusions:

- An increase in cycle pressure ratio to 25-30 from SOA of 10 to 15 provides significant improvement in simple cycle thermal efficiency (≈10%). To provide optimum combined cycle performance it is best to hold at least 1100°F boiler inlet conditions. This higher pressure ratio should therefore be accompanied by a significant increase in firing temperature over current systems to optimize the combined cycle performance.
Figure 1. Simple Cycle Thermal Efficiency versus Turbine Temperature and Pressure Ratio.

- Firing temperature (with underlying assumption of cooling flow increasing with firing temperature) is also a thermal efficiency driver. As will be shown in the body of this report, Allison has advanced hot section technology in development that can significantly reduce required coolant flows at high firing temperatures, thus improving thermal efficiency of the simple cycle.

- High firing temperatures provide high specific power engines. Although engine physical size per se may not be a factor in utility installation, capital purchase cost of utility turbines is a major factor. A 40% increase in specific power results in a 20% dimensional decrease in compressor systems. Turbine stages are even more strongly affected due to increased gas pressures. Component dimensions are a significant cost driver of utility gas turbines.
Critical Technologies

Twenty-five to thirty pressure ratio compression systems are within the realm of current aircraft engine technology. This technology applied to large utility engines can yield high pressure systems at high efficiency.

Turbine technology is critical to advanced turbine systems. The required performance of utility turbines not only includes efficiency but also blade and vane life beyond aircraft engine experience. Reliability and maintainability of the system are critical. Accomplishment of these goals will require the following:

- advanced turbine blade/vane cooling systems and/or ceramic airfoils
- single crystal materials
- active turbine tip clearance control
- liquid/air cooling of vanes

Allison has been developing the Lamilloy® cooling technology for a number of years and has successfully applied

*Lamilloy is a registered trademark of General Motors Corporation.

Figure 2. Lamilloy Concept for Advanced Cooling System
the concept to many systems. Lamillloy approaches transpiration cooling effectiveness. Figure 2 shows a cross section of sheet Lamillloy. Allison is currently developing the technology required to cast single crystal blades in a pseudo-Lamillloy one-piece structure called Castcool®*. Allison has applied the Castcool process to this reference system turbine design.

**Single Crystal (SX) Materials**

New generations of single crystal materials offer significantly improved strength over previous generations which themselves far exceeded the strength of current aircraft materials such as Mar-M247 (Figure 3). These materials represent the potential for significant turbine coolant airflow reduction from current systems. Oxidation/corrosion resistance is vital to success. Figure 4 shows that SX materials can have excellent oxidation properties. Proper coatings or even the need for coatings are issues to be addressed.

*Ccastcool is a registered trademark of General Motors Corporation.

**Ceramic Airfoils**

The DOE's Advanced Turbine Technology Applications Program (ATTAP) initiative at Allison has proven ceramic hot section technology for automotive application. These materials, processes, and design systems are ready for transition to larger components. Figure 5 shows a summary of ATTAP results. Ceramic turbine rotors have demonstrated relatively long life, FOD resistance, and 2500°F uncooled temperature capability (Ref 1).

**Active Clearance Control**

Allison has demonstrated the ability to move high speed rotor systems to control compressor impeller clearances (Ref 2). Figure 6 shows a schematic of the test apparatus. This technique can be applied to larger industrial size engines or even utility size units. The same technique can be applied to static structure in the turbine section to control turbine clearances by moving static structure, i.e., shrouds.
CERAMIC WHEEL / METAL SHAFT ASSEMBLY

2500°F @ 100% SPEED

- 1000 hr rotor durability test completed
- Over 16,000 ceramic component test hours
- Tip rub survivability demonstrated
- Rotors, scrolls, vanes, and combustion in durability test

Figure 5. ATTAP Contract DEN 3-336 Demonstrates Ceramic Technology

Figure 6. Active Tip Clearance System 250-C30 Compressor
Liquid/Air Cooling of Vanes

Allison has demonstrated liquid cooling of airfoils in Air Force/NASA programs (References 3 and 4). Basic research is complete and first order models developed to predict cooling efficiency. Figure 7 shows a schematic of a vane cooled by a water/air mixture.

RESULTS

Allison has studied the impact of these critical technologies on the performance of a utility size unit operating as a combined cycle system. Applying these technologies to the gas generator and combining them with an advanced steam turbine system can result in a system operating at the desired 60% (LHV) thermal efficiency. Table 1 compares key performance parameters of fully developed ceramic and metallic ATS. The ceramic system shows potential for a higher efficiency gas generator at lower turbine temperature than the metallic. The higher exhaust gas temperature of the metallic system into the steam turbine boosts the overall efficiency of the metallic system. The technology and capability of the bottoming cycle thus becomes a key issue in the overall performance levels.

As noted previously, achieving this level of performance requires application of several new technologies. Figure 8 shows the effect on turbine coolant airflow of applying the Castcool technology in single crystal. The combination of these technologies allows higher blade/vane operating temperatures with associated reduction in coolant flows and increased gas generator thermal efficiency.

![Figure 7. Water/Air Mixture as Turbine Vane Coolant Can Reduce Cooling Requirements](image)

<table>
<thead>
<tr>
<th>Table 1. ATS System Performance</th>
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<tr>
<td>Output power—MW</td>
</tr>
<tr>
<td>Thermal effic—LHV</td>
</tr>
<tr>
<td>Gas gen thermal effic—LHV</td>
</tr>
<tr>
<td>Overall press ratio</td>
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<tr>
<td>Total airflow—lbm/sec</td>
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![Figure 8. Turbine Cooling Requirements Versus Airfoil Surface Temperature](image)
The impact of using ceramics in the first blade and second vane is also shown. Note that the impact of ceramics decreases somewhat as higher metal blade/vane operating temperatures become possible through use of single crystal materials.

Table 2 shows the effect of using the Castcool technology versus current technology in the first blade only. Coolant flow is reduced resulting in a nearly 2% improvement in gas generator thermal efficiency.

Active turbine tip clearance control in a five-stage turbine can result in a 2.0 to 4.0% improvement in gas generator thermal efficiency. The 2% improvement results when active control is applied to optimum turbine clearance. Realities of field operation indicate that twice this impact can be achieved because of excess tip clearance due to shroud wear or rub prevention to reduce likelihood of inducing vibratory stress or flutter.

A water/air cooled second turbine vane can be worth 0.6% gas generator thermal efficiency relative to an air cooled vane operating at 1650°F maximum metal temperature (Table 3).

Applying all these technologies to an advanced combined cycle results in the performance levels of Table 1. The goal of 60% (LHV) thermal efficiency is achievable but certainly challenging.

Emissions of HC, CO, and NOx will have to be controlled for the ATS cycle chosen. Allison completed a parametric study using available tools that showed that the required levels are achievable with a high firing temperature cycle. Allison initially "designed" a combustor (which did not meet requirements), then perturbed its

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline cycle Castcool first blade</th>
<th>Baseline cycle with current technology first blade</th>
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</thead>
<tbody>
<tr>
<td>Total output power—MW</td>
<td>194.4</td>
<td>195.6</td>
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<tr>
<td>$\eta$th gas generator—LHV</td>
<td>0.402</td>
<td>0.395</td>
</tr>
<tr>
<td>$\eta$th combined cycle—LHV</td>
<td>0.562</td>
<td>0.557</td>
</tr>
<tr>
<td>Engine mass flow—lbm/sec</td>
<td>641.2</td>
<td>673.0</td>
</tr>
<tr>
<td>Exhaust gas temperature—°F</td>
<td>1115</td>
<td>1086</td>
</tr>
<tr>
<td>$\Delta$% cooling flow</td>
<td>—</td>
<td>+2.59</td>
</tr>
</tbody>
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Table 3. Effect on Performance of Water-Air Cooled Second Vane

Metallic Turbine
Maximum Blade Metal Temperature—1650°F
Engine Size—140 MW Gas Generator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline cycle with air-cooled second vane</th>
<th>Baseline cycle with water-air cooled vane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total output power—MW</td>
<td>194.4</td>
<td>195.6</td>
</tr>
<tr>
<td>ηth gas generator—LHV</td>
<td>0.402</td>
<td>0.4046</td>
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<tr>
<td>ηth combined cycle—LHV</td>
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<tr>
<td>Engine mass flow—lbm/sec</td>
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<tr>
<td>Exhaust gas temperature—°F</td>
<td>1115</td>
<td>1151</td>
</tr>
<tr>
<td>Δ% cooling flow</td>
<td>—</td>
<td>-2.12</td>
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design parameters. As shown in Figure 9, combustor volume and firing temperature are significant NOx drivers. It appears that residence time can be reduced sufficiently to control NOx without causing a significant deterioration in CO output.

FUTURE WORK

Phase I of ATS is complete and proposals for Phase II are due into the DOE in November 1992. Phase II will see more study in at least three basic areas:

- Choice of cycle: lack of customer acceptance of cycles other than the combined cycle system may preclude its use but benefits of other cycles must be more thoroughly defined on an economic basis. A significant cost advantage may outweigh the acceptance problem.
- Bottoming cycle: The advanced combined cycle gas turbine must be studied in context of advanced steam turbine systems. The "right" cycle will be impacted by capability in this arena.

- Hot section technology: regardless of cycle choice the engine hot section is the key to ATS. Allison will work to define the economic payoff of various hot section technologies to initiate design/test of advanced components.
REFERENCES


