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DOE/MC/23165-94/C0237

Advanced Turbine Systems Program

Authors:

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

Contractor:

Allison Gas Turbine Division
General Motors Corporation
P.O. Box 420
Indianapolis, IN 46206

Contract Number:

DE-AC21-86MC23165

Conference Title:

Joint Contractors Meeting: FE/EE Advanced Turbine Systems
Conference, FE Fuel Cells and Coal-Fired Heat Engines Conference

Conference Location:

Morgantown, West Virginia

Conference Dates:

August 3-5, 1993

Conference Sponsor:

U.S. Department of Energy, Morgantown Energy
Technology Center

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CONTRACT INFORMATION

Contract Number	DE-AC21-86MC23165
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 (NO_x), 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*. The 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.

Allison's October 1992 report to this forum concentrated on the turbine technology required to achieve the ATS system. Regardless of cycle type chosen, the hot section, including combustor, was determined at that time to be the key to success.

This 1993 report deals with some of our preliminary screening work done to determine the industrial engine configurations we will want to study under Phase II of ATS Task 6.

PROCEDURE

This preliminary screening effort proceeded in five steps:

1. The basic industrial engine thermodynamic cycles to be studied were chosen
2. The major industrial engine market sectors were determined
3. Applicability of each thermodynamic cycle to each market sector was determined on a global basis
4. Engine thermodynamic cycles applicable to a given market sector were rated against each other on a global basis for that particular market sector
5. Desirable cycle types were determined for several market sectors. These configurations will be studied in detail during ATS Phase II (especially tasks 3, 5, and 6)

The reader is reminded that this is a preliminary screening activity and the real work is to be accomplished under the Phase II ATS effort. These results provide direction to the Phase II work when this effort comes under contract.

THERMODYNAMIC CYCLES

Allison investigated the four basic cycles commonly known and used in our industry. These are:

1. Humid air turbine
2. Intercooled-recuperated systems
3. Simple cycle (with cogen)
4. Chemically recuperated cycle

Initial performance analysis indicates that all have the potential of reaching stated ATS performance objectives. We also concluded in the Phase I study that engine hot section technology would be the critical engine technology regardless of which cycle is chosen for any given market sector. As noted previously, this work was

reported on in detail in the October 1992 Contractor Review Meeting.

Figures 1 through 4 present thermal efficiency capability as a function of turbine inlet temperature for various compressor pressure ratios for cycle types 1, 2, and 3 above. The charts assume use of each of the thermodynamic cycles in the electrical power generating mode. These Figures lead to four conclusions:

1. The ATS advanced technology hot section at 2600°F firing temperature provides significant improvement in thermal efficiency regardless of cycle type chosen. Specific power increases with turbine temperature should result in significant reduction of COE.
2. The combined cycle and the simple cycle optimize at a pressure ratio of approximately 25.

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Figure 1. Simple cycle thermal efficiency versus turbine temperature and pressure ratio.

Figure 2. Combined cycle thermal efficiency—no intercooling.

Figure 4. Intercooled/recuperated/humid air turbine cycle thermal efficiency.

Figure 3. Intercooled/recuperated cycle thermal efficiency.

3. The intercooled-recuperated cycle optimizes at approximately a pressure ratio of approximately 15.
4. The HAT cycle optimizes at a pressure ratio similar to that of the simple and combined cycles; approximately 25.

This type of carpet plot could not be done for the chemical recuperation cycle because of our lack of a recuperator model which could be integrated with Allison's cycle matching modeling system. Several cycles were studied using external iteration. It was concluded that the chemical recuperator and standard recuperation were thermodynamically similar cycles requiring relatively low pressure ratios in order to have high exhaust gas temperatures. Our study resulted in a 2800°F requirement for turbine inlet temperature, 200°F higher than the Allison selected ATS reference cycle, in order to supply the reformer with appropriate gas temperature. A logical but probably less efficient alternative is an auxiliary

combustion system at turbine exhaust to provide adequate reformer inlet temperatures without the high (2800°F) turbine inlet temperature. This cycle has high specific power (output power per unit airflow) similar to the HAT cycle due to the level of steam production in the reformer. Detailed study of this cycle will be accomplished as part of ATS Phase II.

Table 1 presents a summary of performance levels for the various cycles. Thermal efficiency is presented twice; once for the base system and once for the base system with economizer. Site requirements will determine whether an economizer is useful or not. Data in this table are used to rate the engine cycles in terms of fuel efficiency and, secondarily, in terms of specific power which might bear some relation to purchase price.

MARKET SECTORS

Cogeneration is a major market segment. The gas turbine is utilized for production of electrical power along with steam and/or hot water. The steam/hot water are often the primary outputs with electricity of secondary importance. Examples are found in heat intensive

industries such as food processing, chemical, and paper plants.

Pumping of gas in pipelines and compression systems in general is a significant market. The output of the engine is mechanical power. Bottoming cycles are generally not used due to a lack of water at the site, although this can be site dependent.

Generator sets supply prime power without heat recovery. Examples are ship-board power and offshore platform power.

Prime power for marine propulsion is a small but growing market in both commercial and military applications.

Emergency or standby power generation systems such as those used by hospitals are an important market.

APPLICABILITY TO MARKET SECTORS

Table 2 presents a summary of the various engine cycles and their applicability to the major industrial engine market segments. Both the simple cycle and the ICR enjoy wide application capability. Note that in cogeneration-steam Allison sees no substitute for the simple cycle. This same

Table 1.
Fuel efficiency and power density comparison—10-20 MW.

<u>Parameter</u>	<u>Cycle</u>					
	<u>Simple cycle</u>	<u>Cogen steam turb</u>	<u>Cogen hybrid</u>	<u>ICR</u>	<u>HAT</u>	<u>Chem recup</u>
TRIT (°F)	2600	2600	2600	2600	2600	2800
Turbine technology	Metallic/ ceramic	Metallic/ ceramic	Metallic/ ceramic	Metallic/ ceramic	Metallic/ ceramic	Metallic/ ceramic
Thermal eff (LHV)	0.41	0.544	0.48	0.504	0.528	0.541
Specific power	202	267	235	217	312	348
Overall press ratio	25	25	25	15	30	15
Thermal effic with economizer	N/A	0.544	N/A	0.565	0.554	0.554

Table 2.
Industrial ATS application matrix.

<u>Markets</u>	<u>Simple cycle</u>	<u>ICR</u>	<u>HAT</u>	<u>Intercooled chem recuperator</u>
Cogeneration-steam	X + steam generator	O	O	O
Cogeneration-electric	X + steam turbine/hybrid	X	X	X
Compression/pumping	X	X	O	X
Generator sets	X	X	O	O
Marine propulsion	X	X	O	O
Emergency electrical	X	O	O	O

X = applicable

O = not applicable

simple cycle when properly designed can be used in the hybrid mode (steam generation and re-injection) or with a steam turbine for electric power generation.

The HAT and chemical recuperation cycles have only narrow applicability. The HAT cycle, due to its complexity and high water usage, is probably only applicable to electrical generation. The chemically recuperated cycle is limited to those applications where natural gas is readily available as a fuel; i.e. electric cogeneration and gas pumping.

COMPARATIVE UTILITY IN KEY MARKET SECTORS

Table 3 presents the basic purchase decision drivers. Units which do not meet emissions standards (NO_x, CO, HC) will not be sited making this factor a go-no-go gate. There are, however, basic differences such as combustor inlet pressure and temperature and water vapor content. These parameters affect each cycle's inherent ability to meet emission goals and the magnitude of development effort required to do so. First cost (purchase price) or initial in-

vestment has been and is expected to continue as a strong driver in the industrial market. Fuel usage is separated out from the remainder of economics (service, overhaul, cost of money, etc) because it is a major proportion of expenses in any non-standby application.

Table 4 shows the result of rating the various engine cycles in electric cogeneration. Note that fuel usage was weighted

Table 3.
Purchase decision drivers—year 2000.

<u>Application</u>	<u>Driver</u>
Cogen-steam generator	Economics
Cogen-steam turbine	Economics
Cogen-hybrid	Economics
Compression/pumping	First cost/ economics
Generator sets	First cost/ economics
Marine propulsion	Economics/ first cost/site
Emergency electrical	First cost

Table 4.
Comparative utility in electric power cogeneration.

<u>Assessment parameters</u>	<u>Cycle type</u>				
	<u>Simple cycle steam turbine</u>	<u>Simple cycle hybrid</u>	<u>ICR</u>	<u>HAT</u>	<u>Chem recup</u>
Emissions	7	9	8	9	10
First cost	7	10	8	6	5
Fuel efficiency (4.0 weight factor with economizer)	36	38	40	36	36
Economics	<u>8</u>	<u>10</u>	<u>6</u>	<u>5</u>	<u>4</u>
Totals	58	67	62	56	55

Rating scale: 10 = best, 0 = worst

heavily in this application. Also note that performance is compared as though all systems were equipped with an economizer; an optimistic assumption for the ICR cycle. Results show that the hybrid simple cycle is the favorite although the ICR and steam turbine versions are very competitive. The hybrid simple cycle requires a high pressure ratio compressor with excellent operating range to surge; a design challenge.

Table 5 shows the result of rating the various applicable cycles in compression/pumping. The outcome is not clear-cut at all. No economizer was assumed and first cost and fuel efficiency were weighted by a factor of 2.0 over other parameters. All three configurations will have to be studied in ATS Phase II. The ideal solution might be to offer standard and chemical recuperation as options off the same engine core. This may be a turbine design challenge due to the additional steam mass flow in the chemical recuperated version. Site conditions may dictate an air-to-air intercooler

which can be a disadvantage with the ICR and chemical recuperator cycles. The

Table 5.
Comparative utility in compression/pumping.

<u>Assessment parameters</u>	<u>Cycle type</u>		
	<u>Simple cycle</u>	<u>ICR</u>	<u>Chem recup</u>
Emissions	7	8	10
First cost			
(2.0 weight factor)	20	16	12
Fuel efficiency			
(2.0 weight factor) (no economizer)	14	18	20
Economics	<u>10</u>	<u>8</u>	<u>6</u>
Totals	51	50	48

Rating scale: 10 = best, 0 = worst

chemical recuperator may have an additional site disadvantage if make-up water is required.

Table 6 shows the result of rating the various applicable cycles in generator sets. The outcome is again not clear-cut but favors the ICR cycle because of fuel efficiency. In particular applications space claim (not rated here) might be a factor.

It is the opinion of the author that ATS technology will not be favored at all in standby or emergency power units. First cost is essentially the only driver. Emissions should not be a factor in the occasional use scenario.

The ICR is currently favored in marine propulsion. A recent Navy competition selected this cycle over others. The ICR in this application has several advantages including water availability for the inter-cooler and specific fuel consumption. Recuperator fouling is a problem which can be alleviated through proper design.

Table 6.
Comparative utility in generator sets.

<u>Assessment parameters</u>	<u>Cycle type</u>	
	<u>Simple cycle</u>	<u>ICR</u>
Emissions	7	8
First cost	10	8
Fuel efficiency (4.0 weight factor) (No economizer)	30	40
Economics	<u>10</u>	<u>8</u>
Totals	57	64

Rating scale: 10 = best, 0 = worst

There appears to be no substitute for the simple cycle with steam generation in the cogen-steam market since steam is, by definition, a valuable product of the cycle.

CONCLUSIONS

Allison draws the following preliminary conclusions from this preliminary design effort:

1. All cycles investigated require a high temperature turbine capability to be developed under ATS.
2. The HAT and intercooled chemical recuperation cycles compete in only a narrow sector of the industrial engine market. This is the result of the complexity and water usage of the HAT cycle and the limitation of the chemical recuperation cycle to applications where natural gas is readily available.
3. From a cycle point of view, the ICR and chemical recuperation cycles are similar. Both optimize at fairly low compressor pressure ratios (~15) because both want high temperature in the exhaust to optimize the recuperation process. Excess steam production with the chemical recuperation process makes it somewhat doubtful that the two recuperation processes are interchangeable from a hardware point of view. Allison intends to perform a global optimization on this cycle during Phase II of ATS.
4. There appears to be no substitute for the simple cycle with steam generation in the cogen-steam market since steam is, by definition, a valuable product of the cycle.

5. Both the ICR and the simple cycle in the hybrid mode or bottoming unit are competitive in electric cogeneration
 - ICR requires a moderate compression ratio ~10-15
 - Bottomed simple cycle:
 - Requires higher optimum pressure ratio ~20-25
 - Offers moderately high exhaust gas temperature for advanced steam turbines where desired
 - Can be used in the hybrid mode as electrical power requirements vary
6. Simple cycle and ICR are favored in compression/pumping.
7. ICR is currently favored in marine propulsion.
8. ATS systems in general will not be favored in standby/emergency power applications for purchase price reasons.

FUTURE WORK

ATS Phase II will allow detailed study of the various industrial markets. The preliminary results of this paper will be used as a starting point. In the final analysis, the product picked for development must pay off. For the manufacturer, projected revenue stream must exceed development costs; and for the customer-revenue stream must return a profit on purchase price.

REFERENCES

Mukavetz, Dale w. et al. *Proceedings of the Ninth Annual Coal-Fueled Heat Engines Contractors Review Meeting*, Morgantown Energy Technology Center, Oct. 1992

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