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DEVELOPMENT OF A 50-KW, LOW-EMISSION TURBOGENERATOR FOR HYBRID ELECTRIC VEHICLES

Patrick O'Brien
Turbogenerator Systems

AlliedSignal Aerospace Equipment Systems
Torrance, California 90509-2960

ABSTRACT

This paper describes the development of a low-emission, 50-kW turbine-driven generator called a turbogenerator. It gives a detailed description of the key design features that benefit hybrid electric vehicles driven in various driving cycles. Although the turbogenerator is designed for hybrid electric vehicles, other applications such as standby and primary electric power generation will benefit from its characteristics. These include very-low-exhaust emissions, low cost, high reliability, high fuel efficiency, compact design, and low noise levels. The turbogenerator is relatively unique in that the turbine wheel, compressor impeller, and electrical generator are all mounted on a single, common shaft which is supported on air bearings. These features eliminate the need for both the gearbox and oil lubrication commonly found on conventional automotive and gas turbine engines. AlliedSignal developed the 50-kW turbogenerator for Ford Motor Company under the DOE Hybrid Electric Vehicle Propulsion Program. The turbogenerator is designed to fit into the engine compartment of a Mercury Sable. AlliedSignal originally proved this innovative concept in an APU development program for the U.S. Army. The unit developed for that program has accumulated over 600 hours of operation in laboratory and Army vehicle tests.

NOMENCLATURE

APU	Auxiliary power unit
ARPA	Advanced Research Projects Agency
ASM	Armored systems modernization
DOE	Department of Energy
ECU	Engine Control Unit
CO	Carbon monoxide
kW	Kilowatts of electrical power
NOx	Oxides of nitrogen
PM	Permanent magnet
TIT	Turbine Inlet Temperature
UHC	Unburned hydrocarbons

INTRODUCTION

Past attempts at applying gas turbine technology to the automotive industry were not successful because of the high cost. This was due to the complexity of a conventional gas turbine and the expensive materials used for the hot-end components. Conventional gas turbines generally employ a step-down gearbox to drive the generators, and an oil system that includes pumps, filters, seals, sumps, and other controls.

In contrast, the turbogenerator, shown in Figure 1, is unique in that the turbine wheel, compressor impeller, and permanent magnet generator are all mounted on a single, common shaft which rotates at over 75,000 rpm and is supported on air bearings. Since air is the bearing coolant and lubricant, oil and the associated lubrication subsystems are not required. Additionally, since the generator is located on the shaft (and rotates at the same speed), no gearbox is required. This eliminates a considerable number of moving parts, which significantly increases

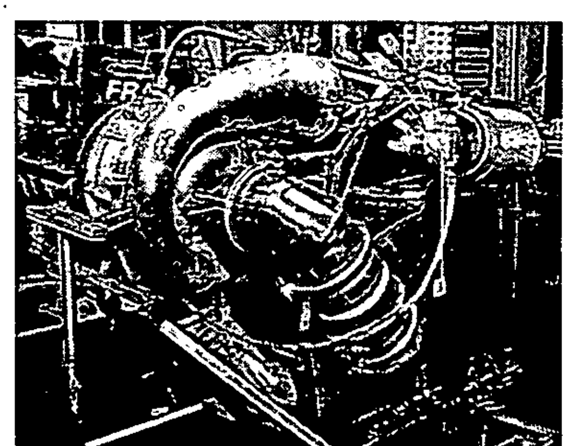

FIGURE 1. 50-KW TURBOGENERATOR

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reliability and reduces cost when compared to a conventional gas turbine or spark ignition engine. The only moving part is the rotor, shown in Figure 2.

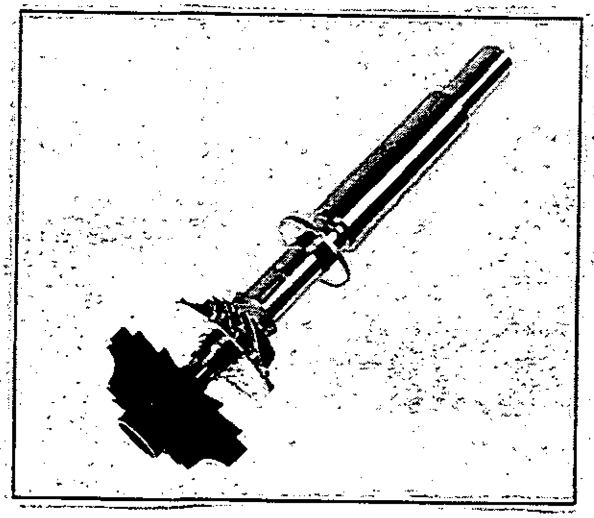

FIGURE 2. 50-KW TURBOGENERATOR ROTOR

The air bearing turbogenerator approach has numerous advantages for automotive applications. Namely, it is a source of auxiliary power that is low in cost, produces very low emissions, consumes little fuel, exhibits high reliability, is small and compact, and operates quietly. The simplicity of the approach described in this paper lends itself to high-volume, low-cost manufacturing similar to that of a turbocharger. The catalytic combustor operates very efficiently at relatively low temperatures, resulting in very low levels of NOx, CO, and UHC. The turbogenerator is a recuperated gas turbine cycle that can achieve greater than 30-percent cycle efficiency in the production configuration.

The elimination of the gearbox and oil lubrication reduces the volume considerably. The air bearings eliminate the oil, which yields significant environmental benefits by reducing national oil consumption and oil waste inherent in conventional engine technology. Approximately 200 million gallons of engine oil are dumped annually by "do-it-yourself" automobile oil changes. This automotive engine does not use lubricating oil, and thus eliminates this hazard.

Previous Experience

This air bearing and PM generator concept is based on the successful APU developed under a U.S. Army contract for the Armored Systems Modernization Program (ASM). The APU program started in 1991 and was completed in 1994. This unit has operated since July 1992, and has accrued over 600 operating hours in laboratory and vehicle tests. It was subjected to endurance tests, multifuel tests, sand and dust ingestion tests, shock and vibration tests, acoustic tests, and performance tests. One APU was installed in a U.S. Army M1A1 main battle tank and tested in several field exercises.

Program Plan

AlliedSignal started work on the automotive turbogenerator in August 1994. The program goals were low cost, low emissions (< ULEV), and high efficiency. The program started with an extensive system and component trade study that resulted in a preliminary baseline design suitable for installation into an automotive engine compartment. The key considerations in this study were low manufacturing cost and low emissions. Compromises in fuel efficiency were made to achieve the low cost and low emissions. Namely, moderate TIT's were employed to allow low-cost turbocharger-type materials, and the use of an ultra-low-emission catalytic combustor. AlliedSignal Turbocharging Systems, with its large-volume, low-cost manufacturing expertise, directed the design and cost effort, as future production will likely occur in the automotive sector of AlliedSignal. The next step was to build the first generation of a producible automotive turbogenerator. This paper largely reports on the Generation 1 effort. Concurrently with the Generation 1 phase, the Generation 2 design was kicked off and two industrial turbogenerator systems (35 and 75 kW) were started. The goals of Generation 2 are higher performance in the same low-cost package.

TURBOGENERATOR DESCRIPTION

System

The 50-kW prototype turbogenerator is a recuperated gas turbine cycle. A diagram of the system is shown in Figure 3.

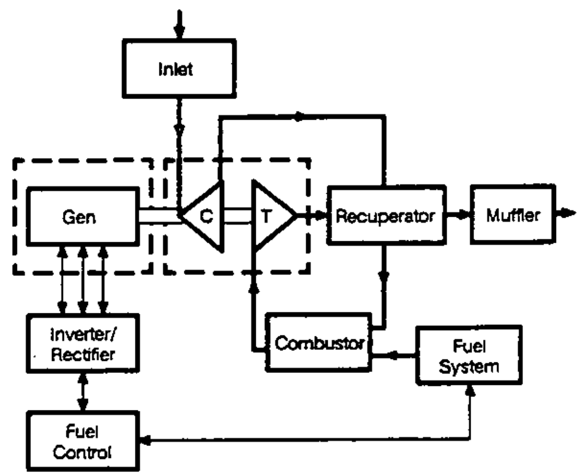

FIGURE 3. SYSTEM DIAGRAM

The basic components are the engine core containing the compressor, generator, turbine, shaft, and bearings; the recuperator; the combustor; the power electronics and fuel control; the fuel system; the inlet filters; and the exhaust muffler. The engine core is shown in Figure 4.

Figure 5 shows a cross section of the turbogenerator. Air from the inlet filter enters the compressor and is compressed up to 3 bar A (45 psia). The compressed air is ducted through the recuperator, where the temperature rises as heat from the turbine exhaust is transferred to the air. This air enters the combustor and is mixed with the fuel and combusted in the catalytic section to produce the high temperatures necessary to drive the turbine. The high-temperature gas is expanded through the rotating turbine wheel, and all the power produced is absorbed by the generator and compressor, which are mounted on the same shaft. The hot gas leaving the turbine wheel passes through the gas side of the recuperator, transferring heat to the compressor discharge air. Table 1 shows the salient operating parameters for the Generation 1 turbogenerator.

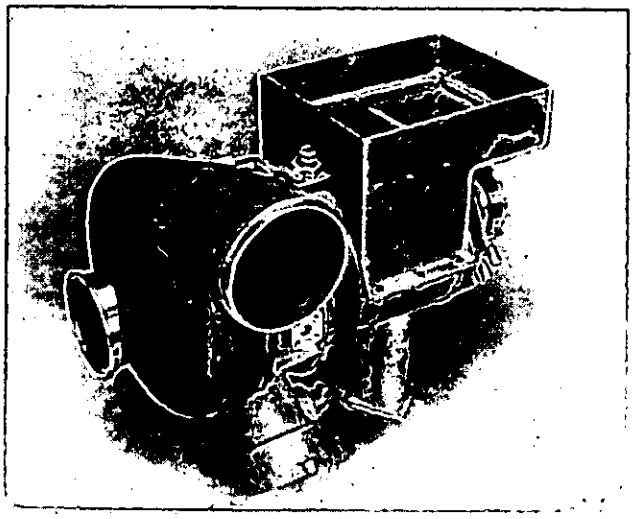

FIGURE 4. ENGINE CORE

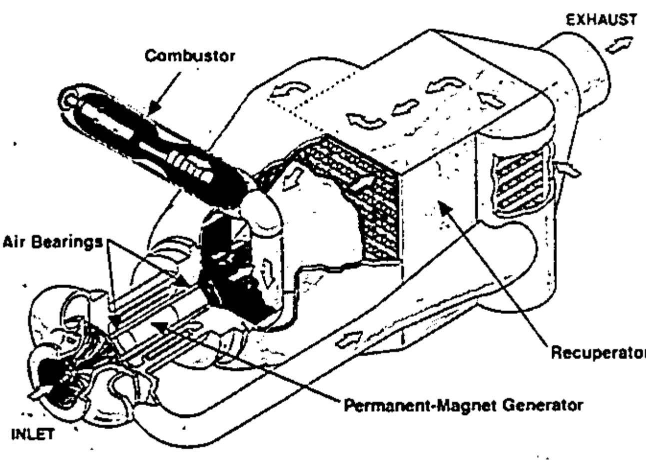

FIGURE 5. TURBOGENERATOR CROSS SECTION

The expected cycle efficiency for the Generation 1 turbogenerator is 26 percent. This includes all losses, from the power to pump in the fuel, to the electrical conversion losses to produce regulated power at 300 vdc. Although the efficiency is too low for production automotive applications, it is sufficient to show the benefits in the near term and resolve integration issues. To expedite early Generation 1 tests, an existing low-performance design was used. The recuperator pressure loss characteristic of this unit was higher than desired. This contributes to the lower cycle efficiency of the Generation 1 turbogenerator.

Rotor/Generator

The rotor shown in Figure 2 consists of the compressor impeller, turbine wheel, and generator. The key features are listed in Table 2. The operating speed is varied with load to obtain the maximum part load efficiency. At 100-percent load, the speed is about 75,000 rpm. The normal operating speed of about 75,000 rpm provides sufficient margin from both bending mode critical speeds to ensure trouble-free operation. A rotor dynamic bode plot is shown in Figure 6.

TABLE 1

SYSTEM OPERATING CONDITIONS
(SEA LEVEL, 75°F)

Speed, rpm	75,000
Electrical power (regulated dc), kW	48.4
Compressor	
Air flow, kg/sec	0.44
Pressure ratio	3.3
Efficiency, percent	77
Recuperator, air-side	
Inlet temperature, °C	183
Exit temperature, °C	677
Combustor	
Fuel	Diesel
Fuel flow, kg/hr	15.7
Turbine	
Inlet temperature, °C	1010
Exit temperature, °C	753
Pressure ratio	2.8
Efficiency, percent	88
Recuperator, gas-side	
Inlet temperature, °C	753
Exit (exhaust) temperature, °C	303
System	
Cycle efficiency, percent	26.2
Specific fuel consumption, gm/kW-hr	325

TABLE 2

ROTOR PARAMETERS

Design speed, rpm	75,000
Mass, kg	8.0
Turbine wheel	
Type	Radial inflow
Diameter, mm	153
Compressor impeller	
Type	Centrifugal
Diameter, mm	117
Generator	
Type	Permanent magnet
Efficiency, percent	93.8
Power, kW	51.0

The generator rotor is located on the right side of the shaft to isolate the magnetic material from the hot turbine wheel. The Generation 1 uses samarium cobalt PM material. The generator performance, shown in Table 2, is based on rectified dc output.

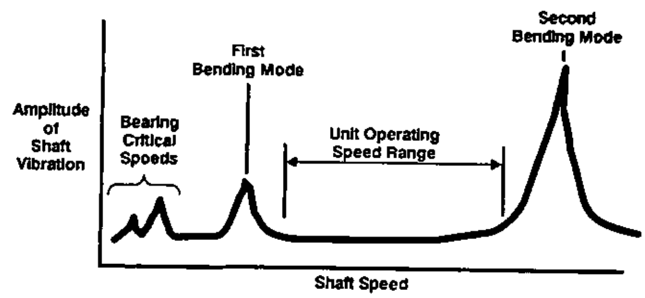

FIGURE 6. ROTORDYNAMIC RESPONSE VS SHAFT SPEED

Bearings

The prototype turbogenerator has one moving part, the high-speed rotating shaft described in the previous section. The shaft is supported on a thin film of air generated by the compliant foil air bearings. These consist of two journal bearings to support radial loads, and two thrust bearings to support axial loads.The bearings are made of thin foil material, as shown in Figure 7. The bearings are hydrodynamic and do not require an external pressurized supply of air. The air pressure is generated by the rotating shaft. As the shaft rotates, it draws the air into the converging wedge-shaped geometry of the foils, which effectively converts the dynamic velocity head into pressure. As soon as the air film is developed, it supports the shaft. Foil bearings consist of self-aligning compliant surfaces, which are relatively insensitive to misalignment and thermal distortion. Excellent damping is provided by the coulomb friction that develops where the overlapping foils contact one another and the retainer.

Normally, the shaft is supported on a thin film of air and does not contact the stationary bearing surface, except during startup and shutdown. Bearing life depends on the number of stop/start cycles incurred. Bearings similar to those used in the Generation 1 turbogenerator have been cycled through 100,000 start/stops without showing excessive wear. This is considerably more than required for an adequate service life.

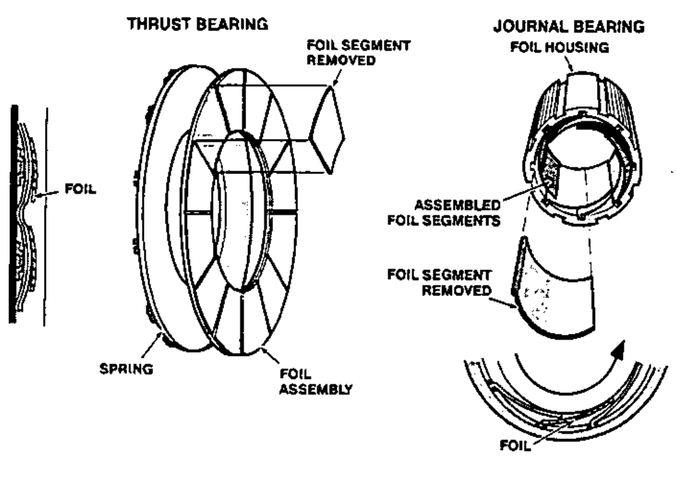

FIGURE 7. FOIL AIR BEARING DIAGRAM

These unique air bearings are not a new technology. AlliedSignal has been developing compliant foil air bearings since 1957, and has incorporated them on aircraft and ground vehicle cooling turbines. Over 45 types of aircraft use foil bearings, including the DC-10, 767, 757, F-16, F-18, and ground-based applications such as the M1A1 main battle tank. AlliedSignal has produced over 13,000 foil bearing turbomachines that have accumulated over 250,000,000 operating hours.

Combustor

The combustor, shown schematically in Figure 8, raises the gas temperature from 677° to 1010°C, as required for the turbine to sustain steady-state operation. The catalytic combustor is able to burn very lean fuel/air mixtures, resulting in an adiabatic flame temperature below NOx-forming temperatures, while still attaining high combustion efficiency (>99.5 percent) in a small combustor. The estimated steady-state emission levels are shown in Table 3.

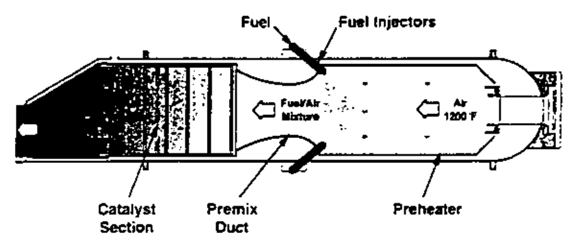

FIGURE 8. CATALYTIC COMBUSTOR DIAGRAM

TABLE 3

ESTIMATED STEADY-STATE EMISSION LEVELS

NOx	2 ppm
UHC	2 ppm
Corrected to 15 percent O_2	

The Generation 1 turbogenerator will operate on diesel fuel, although the catalytic combustor is suitable for operation on gasoline, alcohol fuels, and natural gas. The catalytic combustor consists of three sections: the catalyst section, the prevaporizing and premixing section, and the preheater. For sustainable catalytic combustion to begin, the catalytic section must be heated to at least 500°C. During a cold start, this is accomplished by the preheater. The preheater is a lean diffusion flame combustor that only operates for a short period of time until the catalyst section heats up. This type of preheater was chosen because it generates the quantity of heat required for rapid starts. The Generation 1 turbogenerator can be started in 20 sec; future versions will start even faster (approximately 10 sec). When the catalyst section has reached 500°C, premixed and vaporized fuel is introduced into the premixing section. The ensuing reaction raises the temperature to 1010°C. Both steady-state and startup emissions were considered in the design to ensure low emissions over the complete driving cycle.

Recuperator

The Generation 1 turbogenerator uses a fixed-boundary, plate-fin, metallic recuperator, shown in Figure 9. The fixed-boundary design eliminates the inherent leakage between the high- and low-pressure sides of a rotary regenerator. The Generation 1 unit was fabricated from stainless steel, has a mass of 73 kg, and offers an effectiveness of approximately 0.86. Much of the material selection and joining technology was derived from AlliedSignal experience with industrial and shipboard gas turbine recuperators.

Electronic Controls

The electronic controls have three functions:

(1) Control the operation of the turbogenerator

(2) Operate the generator as a starting motor during turbogenerator startup

(3) Rectify and control the voltage produced by the generator

To accomplish the first function, the Generation 1 turbogenerator uses a digital electronic engine control unit (ECU). This design was based on technology derived from AlliedSignal aircraft engine controls and automotive anti-lock braking experience. This fuel control is shown in Figure 10. This controller supervises and controls the startup, shutdown, steady-state speed, and protection circuits. It obtains feedback on rotor speed and turbine temperature, and it commands both the flow of fuel to the catalytic combustor and the operation of the startup inverter.

During startup, the inverter draws current from the dc power bus and drives the generator as a motor. When the rotor speed reaches 40,000 rpm, the inverter shuts off, and the rotor is accelerated by the heat from the combustor. When the turbogenerator has reached full speed, current starts flowing back onto the bus from the generator.

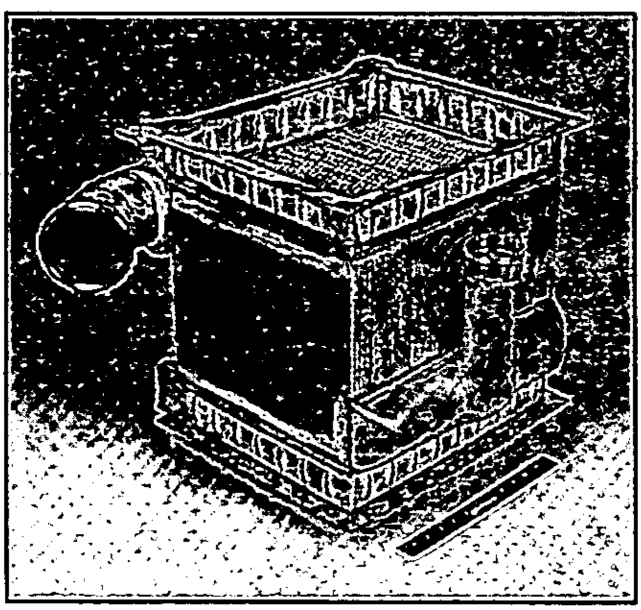

FIGURE 9. GENERATION 1 RECUPERATOR

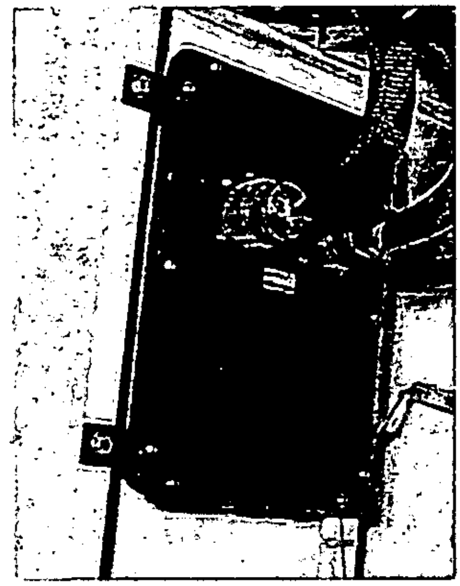

FIGURE 10. DIGITAL ENGINE CONTROL UNIT

TURBOGENERATOR TESTS

Component and system tests are described in this section. The component tests included rotordynamic testing, air bearing tests, turbine and compressor performance tests, generator performance, catalytic combustor and preheater tests, and recuperator performance. The system tests included startup, steady-state and transient operation, emissions, and performance. The engine core, combustor, and system tests will be discussed in this paper.

Engine Core Development Tests

The rotordynamics were tested to measure the response of the shaft as it transversed the first bending critical speed. Various levels of balance and rates of acceleration (through the critical speed) were tested. A 1,000-cycle test (through the first shaft bending critical speed) was performed with no change in rotordynamic characteristics throughout the test. A posttest inspection of the unit showed the shaft and bearings to be in excellent condition.

The permanent magnet generator has undergone a set of development tests in a component test rig. The purpose is to characterize the power generation of the electromagnetic component alone. The rig allows for the breakdown of the iron and copper losses. The copper losses were the same as the predicted values and the iron losses were within 10 percent of the predicted value.

Turbine and compressor aerodynamic testing included efficiency and flow as a function of pressure ratio and speed. Turbine wheel burst and containment tests proved the design integrity of the static structures. The air bearings have been tested on specially designed rigs that measure damping, load capacity, start torque, and power loss at design speeds.

Catalytic Combustor Development Tests

The combustor tests consisted of steady-state operation and simulated startup with preheater. Most of the testing was conducted with diesel fuel, but some data were taken with propane, JP-4 jet fuel, and unleaded gasoline. The results of the initial steady-state testing, performed with a fully mixed and vaporized propane/air mixture, are shown in Table 4. Further tests were conducted on DF-2 diesel fuel and gasoline. These results are also shown in Table 4.

TABLE 4

COMBUSTOR TEST RESULTS
STEADY-STATE EMISSIONS

	Predicted Emissions	Propane Test (1)	DF-2 Test (2)	Gasoline Test (4)
NOx, ppm	2	< 1	3	4
UHC, ppm	2	< 1	9	4
Corrected to 15 percent O_2				

NOTES:

(1) Catalytic pipe rig test, 1000°C exit temperature
(2) Test 4, configuration 1, 1009°C exit temperature
(3) Test 4, configuration 2, 1012°C exit temperature

The production of NOx emissions was found to be almost entirely a function of the nitrogen content of the fuel. For low nitrogen gasoline, measured NOx was less than 2 ppm (corrected to 15 percent O_2) while for relatively high nitrogen content DF-2, NOx increased to about 14 ppm. CO levels varied between 100 and 1000+ ppmv. This characteristic is attributed to low residence time prior to measurement. The effects of continued reaction downstream of the combustor are currently under investigation. Approximately 50 hours have been logged on various catalytic combustors used for development testing.

Turbogenerator System Development Tests

The Generation 1 system testing began in October 1996. Catalytic combustor testing was not performed in the early system test because the startup and fuel control logic development was the primary objective. However, the combustor being used was the same as the Generation 1, except the catalyst substrates were not coated with catalyst. The low-emission preheater was run continuously to perform startup and fuel control tests.

The engine control unit demonstrated the ability to control the engine speed with the generator load via the power electronics unit. This novel fuel controls approach allows the system to run with constant TIT needed for the catalytic combustor, but also results in high system efficiency at part load conditions. The Generation 1 system steady-state tests were conducted at speeds up to 78,400 rpm and TIT's up to 1010°C.

The catalytic combustor, with a new set of catalyst discs furnished, was installed in the turbogenerator engine on the laboratory test stand in March 1997. Testing was conducted over the course of the following month, during which the catalyst was operated for 8 hours, and 12 transitions were made from preheater to catalytic operation. All engine starts were made using the preheater, and transitions to catalytic operation occurred after warm-up. There was no evidence of flashback or autoignition within the premix duct during the testing, based on measurement of the duct skin temperature. DF-2 diesel fuel was used for all engine testing.

Emissions were measured at a point about 2 cm downstream of the catalyst exit, at the turbine exit, and in the engine exhaust tailpipe about 1 m downstream of the recuperator hot-side exit. Engine tailpipe emissions are summarized in Table 5. The table shows volume parts per million for the emissions constituents corrected to 15 percent O_2.

TABLE 5

GENERATION 1 ENGINE TEST DATA

	PPMV, 15 percent O_2
NOx	6
CO	97
HC	0
Combustion eff.	0.999
Temperature, °C	1013

The combustor has been extensively tested in both a rig and the turbogenerator engine. In the engine testing, steady-state emissions of NOx, CO, and unburned hydrocarbons were demonstrated that were significantly lower than the ULEV standards. Transient emissions of the preheater were measured on the rig that were also competitive with ULEV. NOx emissions in particular were found to be very low over the full operating range of the catalytic combustor, and in fact were shown to be almost strictly a function of the nitrogen content of the fuel.

CONCLUSION

The turbogenerator described in this paper eliminates the major hindrances to using gas turbine technology in automotive applications. The elimination of all but one moving part inherently increases reliability and reduces cost, when compared to a conventional gas turbine. The air bearing turbogenerator approach has numerous advantages including low cost, low exhaust emissions, low fuel consumption, high reliability, compact size, and quiet operation. The simplicity of this turbogenerator approach lends itself to high-volume, low-cost manufacturing, resulting in a clean source of efficient power at low cost.

The 50-kW turbogenerator program at AlliedSignal will continue to develop this significant low-cost technology through a multi-step program in partnership with major automobile manufacturers. The goals of the Generation 1 turbogenerator are to achieve 48 kW, ULEV emissions, and 26-percent cycle efficiency. Concurrently, a second generation turbogenerator is being developed and is scheduled to go into test in mid 1998. The goals of this turbogenerator are to achieve 50 kW, and ULEV emissions.

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