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THERMOELECTRICAL ENERGY RECOVERY FROM THE EXHAUST OF A LIGHT TRUCK

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ABSTRACT

A team formed by Clarkson University is engaged in a project to design, build, model, test, and develop a plan to commercialize a thermoelectric generator (TEG) system for recovering energy from the exhaust of light trucks and passenger cars. Clarkson University is responsible for project management, vehicle interface design, system modeling, and commercialization plan. Hi-Z Technology, Inc. (sub-contractor to Clarkson) is responsible for TEG design and construction. Delphi Corporation is responsible for testing services and engineering consultation and General Motors Corporation is responsible for providing the test vehicle and information about its systems. Funds were supplied by a grant from the Transportation Research Program of the New York State Energy Research and Development Authority (NYSERDA), through Joseph R. Wagner. Members of the team and John Fairbanks (Project Manager, Office of Heavy Vehicle Technology under Department of Energy) supplied cost-sharing and in-kind support.

Currently, the design of TEG has been completed and initial construction of the TEG has been initiated by Hi-Z. The TEG system consists of heat exchangers, thermoelectric modules and a power conditioning unit. The heat source for the TEG is the exhaust gas from the engine and the heat sink is the engine coolant. A model has been developed to simulate the performance of the TEG under varying operating conditions. Preliminary results from the model predict that up to 330 watts can be generated by the TEG which would increase fuel economy by 5 percent. This number could possibly increase to 20 percent with quantum-well technology. To assess the performance of the TEG and improve the accuracy of the modeling, experimental testing will be performed at Delphi Corporation. A preliminary experimental test plan is given. To determine the economic and commercial viability, a business study has been conducted and results from the study showing potential areas for TEG commercialization are discussed.

1. INTRODUCTION

A typical energy path in a gasoline fueled internal combustion engine vehicle is shown in Fig. 1. Up to 40 percent of the energy rejected leaves in the exhaust [1]. Furthermore, the exhaust temperature is much greater than that of the other heat rejection streams. Therefore, the potential conversion efficiency of a bottoming cycle connected to this stream is the largest.

Clarkson University has formed a team to develop, install, and test a prototype thermoelectric generator (TEG)-based exhaust energy recovery system from a light truck. The project is a joint effort between Clarkson University, Hi-Z Technology Inc., Delphi Corporation and General Motors Corporation.

In the following we begin with a discussion of the project motivation and objective, then discuss the TEG design and system modeling. Preliminary results from the system modeling are discussed and an experimental plan to validate these results is proposed. We also present the principal conclusions of a market survey done for the project draft commercialization plan.

1.1 Motivation

Apart from potential commercial benefits, many environmental and socio-economic aspects can be attributed for the start of the project. A few of these are as follows:

- "Despite an increasingly energy efficient economy the U.S remains dependent on foreign oil. Of the 19.5 million barrels of oil Americans consume everyday, about 11.5 million are imported. Roughly half the oil consumed in the U.S goes for cars and trucks" [2].
- "The United States has the highest rate of carbon emissions in the world. One-third of these are transportation related. Carbon emissions are increasing because of the failure to improve the fuel economy of vehicles. With carbon dioxide being the dominant green house gas, vehicle emissions is a significant cause for global warming" [3].
- Increasing electrical loads: future automobiles must generate more power to support features such as collision avoidance systems, vehicle stability control, navigation etc, while reducing fuel consumption and emissions.
- Corporate average fuel economy (CAFE) regulations: truck CAFE has been increased for the period 2005 to 2007, from 20.7 mpg today to 22.2 mpg in 2007. Car CAFE has not been changed for many years. But Congress has charged National Highway Transportation Safety Authority (NHTSA) with a study and recommendation for car CAFE increases. Therefore any technology that might improve the fuel economy may be very important to the automotive companies to enable them to meet the increased CAFE requirements.
- Currently the Federal Test Procedure (FTP) for establishing the fuel economy for CAFE and "window sticker" on vehicles, includes a very low electrical load (250 W), because no accessories or lights are on during the test. In actual operation a driver has many electrical loads, lights, fans for AC or heat, radio, electrical power steering, etc, that could be 700 to 1500 watts. Therefore if this gets updated, it will be a big challenge for the automotive companies to meet these requirements.

1.2 Project objective

Demonstrate the feasibility of a prototype TEG for a passenger vehicle, to offset the shaft power consumed by the alternator. The TEG must be capable of generating a net 330 watts of power and supply it to the vehicles 12 volt electrical bus. This should result in a fuel economy increase up to 5 percent for a typical driving cycle. The savings could be up to 20 percent with quantum-well thermoelectrics.

2. TEG DESIGN

To understand the design decisions it is best to start with an understanding of the thermoelectric modules. The thermoelectric modules will be the High-Z Technology HZ20, a 72-couple design using bismuth telluride technology. Fig. 2 shows this module and some of its properties. An efficiency close to 5 % is attainable as shown in Fig. 3.

Fig. 4 shows a plot of power versus temperature difference. This figure shows that for a fixed cold-side surface temperature, the power generated increases with an increase in temperature difference across the module, and for a fixed temperature difference across the module the power generated is highest for the lowest cold side surface temperature. Therefore for maximum power we need a design that maximizes the temperature difference across the module and minimizes cold side temperature. This does not give maximum efficiency, but our interest is in maximum power.

2.1 TEG System physical layout

The design that we arrived at based on these considerations is shown in Fig. 5, the assembled thermoelectric generator without its case. The TEG system includes the Exhaust gas heat exchanger, counter flow coolant heat exchangers, sixteen series connected HZ20 thermoelectric modules, and the power conditioning unit (not shown in the Fig. 5).

The exhaust gas temperature that the TEG receives is determined by the location of TEG within the exhaust section. As shown in Fig. 6, for the test vehicle, GMC Sierra 1999, the exhaust gas from the engine comes out from the two exhaust headers, and then flows through the right and left catalytic converters. As discussed in the previous section, to achieve high exhaust gas temperatures the thermoelectric generator must be located just downstream of the exhaust headers. But there is concern that the generator, if located upstream of the catalytic converters, would increase the warming time of the catalytic converters, thus increasing the pollutants discharged while the converters are warmed. Also, in order to achieve the design power the generator would have to be made in two sections, one for each header. The space around the pipe sections between the crossover and the converters was also very small, and would also require two generator sections. The location shown in Fig. 7 between the two cross members, to the right of the drive shaft, and to the left of the frame had enough room. In this space, there is 15.6 inches between the drive shaft and the right side of the frame.

2.2 Coolant system

Engine coolant has been preferred over air-cooling as a source for the heat sink to enhance the heat transfer rate. A counter flow arrangement has also been used to enhance the heat transfer rate and to have a uniform temperature difference along the length of the heat exchanger. The TEG system design requires the coolant flow to be continuous, but because of the coolant system layout within the test vehicle, the tap at the heater core shown in Fig. 6 is the only feasible location for obtaining a continuous flow.

To achieve maximum power the cold side temperature should be minimized. Low coolant temperature can be obtained by pre-cooling of the engine coolant before it enters the TEG with the help of a heat exchanger as shown in Fig. 6.

2.3 Power conditioning unit

Due to the varying operating conditions of the vehicle, the output voltage generated by the TEG is variable. However, the vehicle electrical system requires a constant stable input to its bus. A power conditioning unit overcomes this problem by incorporating a buck-boost converter.

3. SYSTEM MODELING

The system modeling can be divided into four sections: (1) exhaust system (2) coolant system (3) TEG and (4) electrical system.

3.1 Exhaust system

A one-dimensional exhaust system energy model accounts for temperature loss from the exhaust gas through the exhaust pipe before it enters the TEG. It calculates the inlet temperature of the exhaust gas into the TEG. It also includes a model that takes into account the effect of insulating the exhaust pipe.

3.2 Coolant system

The coolant system is modeled using one-dimensional, lumped flow resistances. Given the rotational speed of the engine, the coolant system model predicts (a) flow through the TEG, the radiator (if the thermostat is opened), and the heater. With this coolant model we can account for the additional pumping power required for the coolant flow through the TEG.

3.3 TEG

The model for the TEG is a coupled system between the exhaust gas heat exchanger, the coolant heat exchangers and the thermoelectric modules. The critical area is the modeling of the heat exchangers. Currently we are using (Kays, W.M., and London, A.L., Compact Heat Exchangers) [4] to estimate the heat transfer coefficients. Given the inlet temperature and mass flow rate of exhaust gas and coolant, the model predicts (a) exhaust gas and coolant outlet temperatures (b) module surface temperatures (c) current, voltage and power produced by TEG, when coupled to IV characteristics of the vehicle's electrical bus.

3.4 Electrical system

The electrical system contains models for the alternator, the electrical loads on the test vehicle, the battery, and the power conditioning unit. Given the voltage and current generated by the TEG, it predicts the voltage and current output from the power conditioning unit, taking into account the total load on the system and the efficiencies of various components of the system.

3.5 Simulation platform

The modeling is being done using Matlab® and Simulink® and the developed model has been integrated into ADVISOR (Advanced Vehicle Simulator), developed by National Renewable Energy Laboratories. ADVISOR is a set of model, data, and script text files for use with Matlab® and Simulink®. It is designed for rapid analysis of the performance and fuel economy of conventional, electric, and hybrid vehicles. ADVISOR provides the exhaust gas mass flow rates and exhaust gas temperatures, which are furnished to the TEG model to predict the power production. This in turn is furnished to ADVISOR's alternator model resulting in the reduction of the load on the alternator, and subsequently on the engine. ADVISOR then predicts the fuel consumption and vehicle emissions based on the new load on the engine. By comparing the simulations of baseline (simulation performed without the presence of TEG on the vehicle) and with the TEG, we are able to estimate the amount of fuel savings and the reduction in emissions.

3.6 Simulation results

We have preliminary results from the simulation. Before presenting these results, we would like to state that many of the parameters of the model need experimental verification. The heat transfer coefficients for the heat exchangers and use of constant alternator efficiency are two examples. Because of this, the results of simulation could be significantly different in magnitude than what is observed experimentally.

A plot of sensitivity of power generated by thermoelectric generator to coolant mass flow rate is shown in Fig. 8. From the plot we observe that for coolant flow rates starting at 0.2 kg/s (location of star mark in Fig. 8) and above the power generated by thermoelectric generator tend to remain constant. Therefore we can infer that coolant mass flow rate of about 0.2 kg/s might be sufficient to generate the required power of 330 watts, thereby reducing the amount of additional load on the coolant pump to generate the required amount of coolant flow through the TEG.

Fig. 9 shows a plot of percent fuel savings versus alternator system efficiency. There are two curves, the upper one represents the highway driving cycle and the lower represents the urban driving cycle. From the plot we observe that for both highway and urban driving cycles the percent fuel savings increases as the alternator efficiency decreases and the percent fuel savings is greater for highway driving cycle. A typical number for alternator system efficiency is about 50 percent at medium speeds [5].

4. EXPERIMENTAL TESTING

We will perform experimental testing at Delphi Corporation. Some of the objectives of the test plan are: (1) to determine the fuel savings, reduction in emissions, power produced, and efficiency of the TEG, (2) to validate the simulation code, and (3) to determine the effect of the TEG on the performance of other systems. For example one such interesting area is the coolant system. The TEG imposes an additional heat load on the radiator. Also there might be an increase in the time that the thermostat valve is open, and additional pumping power required for the coolant flow through the TEG.

We will test with and without the TEG. Fig. 10 shows the replaceable section of the exhaust pipe, which is about 27 inches in length. Towards the left is the ball flange and right end of the exhaust pipe is connected to the muffler. A flanged joint will be installed in front of the muffler. Therefore the muffler front section can be easily replaced with a section containing the TEG during the experimental testing.

The parameters to be measured at different locations, shown in Fig. 11 are: temperature of the exhaust gas, coolant and thermoelectric module surfaces, the mass flow rates of the exhaust gas and coolant, gauge and differential pressures for the assessment of back pressure and estimation of loss coefficients of components, current and voltage measurements for use in power and efficiency calculations, and torque, RPM and fuel consumption for calculation of the power of the vehicle and the fuel savings and reduction in emissions.

5. BUSINESS STUDY

A business study was conducted to determine the economic and commercial viability of the TEG. A few results from this study are shown in Figs. 12, 13, and 14. In each of these figures a plot of dollar savings on fuel vs. vehicle life is shown. The lower three set of lines represents 5 percent fuel savings with current thermoelectric technology. Whereas the upper three set of lines represents 20 percent fuel savings with quantum well thermoelectrics. Estimates have been made for three different fuel prices of $ 1.5, $ 2.0, and $ 2.5 per gallon respectively. Estimated average TEG system cost is about $ 500, this can be reduced to as low as $ 200 if installed when producing vehicles in large quantities.

Fig. 12 pertains to passenger cars traveling 6000 miles traveled per year per car. With $ 500 as the TEG system cost, the break-even point with current thermoelectric technology varies from 20 to 30 years for a fuel price varying from $2.5-$1.5 per gallon. Whereas with quantum well thermo electrics which offers 20 percent fuel savings the break even point can be as low as 5 to 10 years for the three different set of fuel prices.

Fig. 13 pertains to light trucks. Most of the results in this category are similar to that of a passenger car with slightly higher amount of dollar savings and lesser number of years required for break-even.

Fig. 14 refers to commercial fleets traveling 65,000 miles per vehicle per year. Even with current thermoelectric technology the number of years required for break-even is extremely low compared to other two categories, about 1.5 years. The market for this group of vehicles is very promising. With quantum well technology offering 20 percent fuel savings and say a gasoline price of $ 2 per gallon in the near future, savings for five years is about $ 6000 on a single commercial fleet vehicle. The installation cost is dwarfed by the savings.

6. DESIGN ISSUES

The TEG reduces exhaust noise [6]. Therefore a combination of TEG and muffler may be possible. As discussed earlier for higher power generation the thermoelectric modules should receive high exhaust gas temperatures. Therefore a design which combines a TEG with the catalytic converter, or one locating the TEG on the engine exhaust headers, also should be explored.

Opportunities to recover thermal losses as electrical energy exist in each of the three loss paths, exhaust, engine block, and radiator. Clearly such designs require the TEG to be incorporated at the beginning of vehicle design, rather than as an add-on.

7. FUTURE STUDIES

Studies involving modeling verification, application of TEG to hybrid electric vehicles etc, system optimization studies, and final commercialization plan will be performed in the next phase of this project. An overview of these studies is as follows:

7.1 Final model verification

A comparison between predictions of the system modeling and experimental test results will be performed, and shall improve the system model as required to increase its accuracy.

7.2 Alternative vehicles

With the hybrid electric vehicles offering practical benefits like improved fuel economy and lower emissions compared to conventional vehicles, it seems that hybrids are taking center stage. We will conduct a study of TEG applied to these new generation vehicles. We are also interested to know about the practicability of application of TEG to natural gas fueled generator.

Also we would like to study the performance of TEG on current generation vehicles, hybrid electric vehicles and natural gas fueled generators using quantum well thermoelectric modules, under the assumption that quantum well technology will be commercially available.

7.3 System optimization study

Using the improved system modeling as a tool, studies will be performed for improvements in the heat exchanger: increasing the overall heat transfer coefficient and area product while minimizing weight, cost and pressure drops. Studies on different models using air cooling (source for the heat sink) as an alternative for the engine coolant will be performed.

7.4 Final commercialization plan

The study will include findings and recommendations about TEG commercialization.

8. CONCLUSIONS

Experimental testing will be an important phase of the project. It will show the effect of the TEG on different systems of the automobile, and will validate the simulation code. The results of the business study have shown that commercial fleets are a potential market for the TEG. Emphasis has to be laid on exploring different feasible options for the source of heat sink, because of additional pumping power required for the coolant flow through the TEG, thereby reducing the net saving in power achieved by the TEG.

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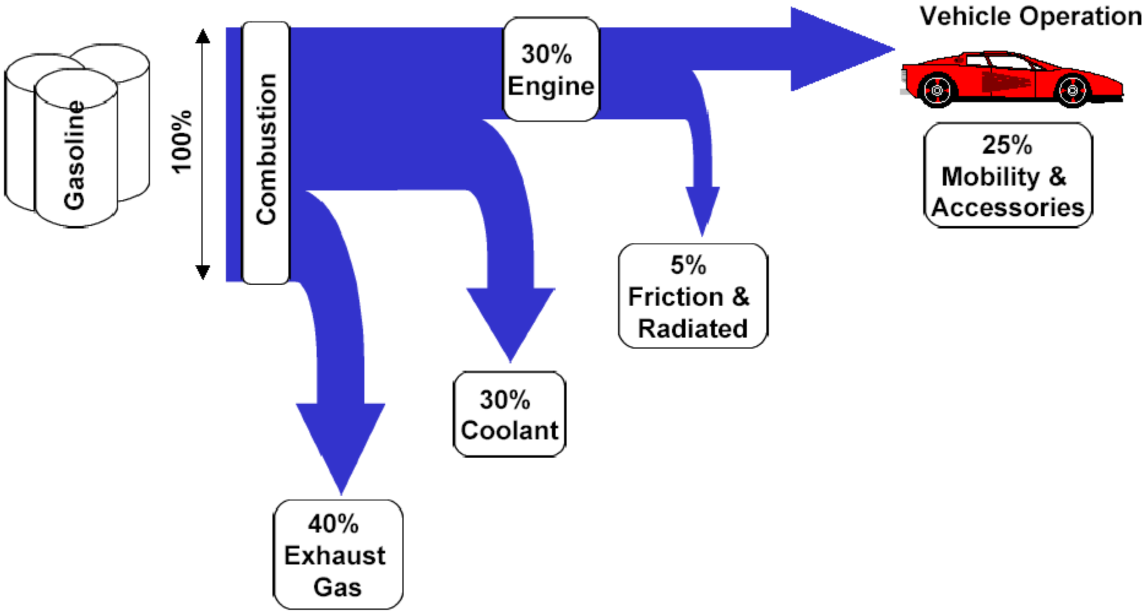
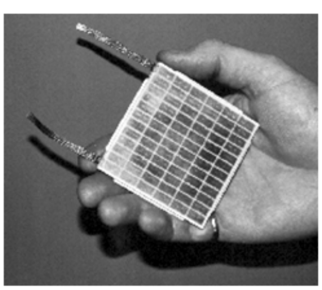


Fig.1 Energy path in gasoline fueled internal combustion engine vehicle [1].



	Value
Thermal Properties	
Design hot side temperature	**230 C**
Design cold side temperature	**30 C**
Maximum continuous temperature	**250 C**
Maximum intermittent temperature	**400 C**
Electrical properties at design temperatures	
Power	**19 Watts**
Efficiency	**4.5 %**

Fig.2 HZ20 thermoelectric module properties at design conditions.

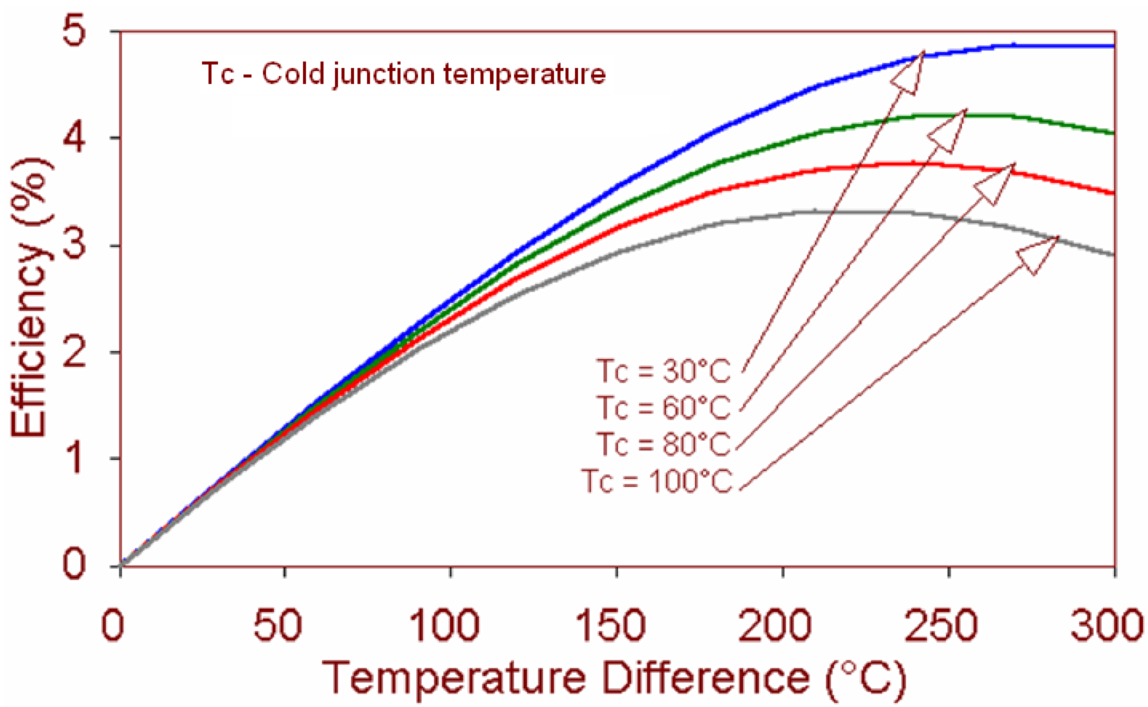


Fig.3 HZ20 thermoelectric module efficiency curves.

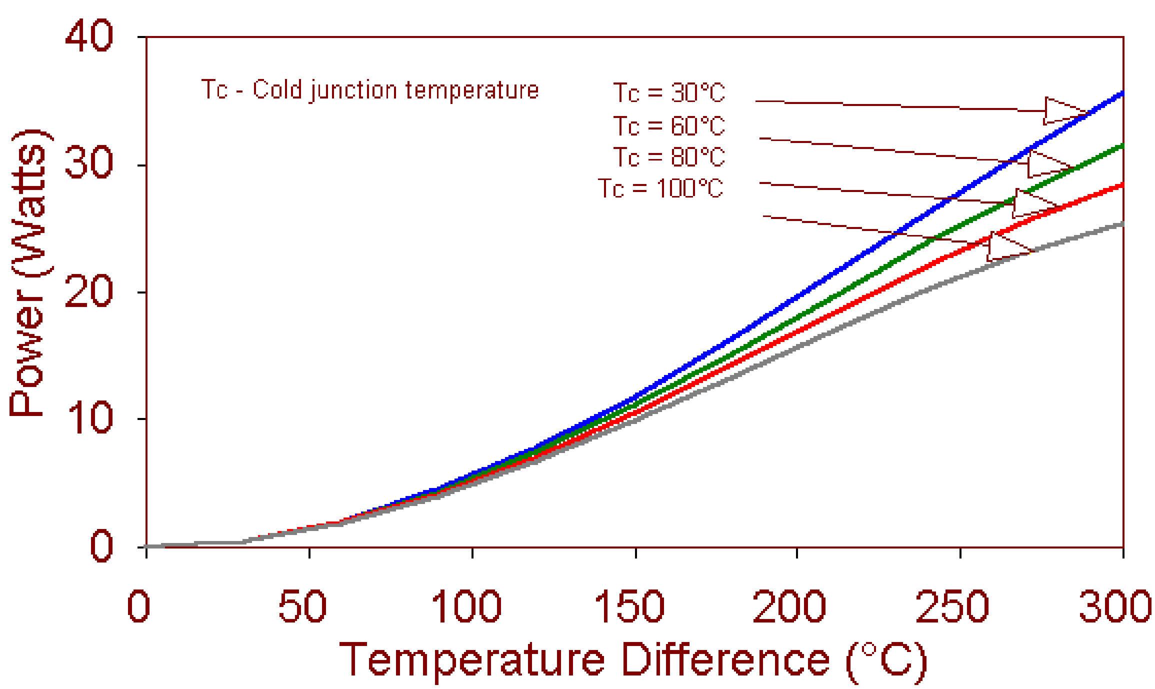


Fig.4 HZ20 thermoelectric module power curves.

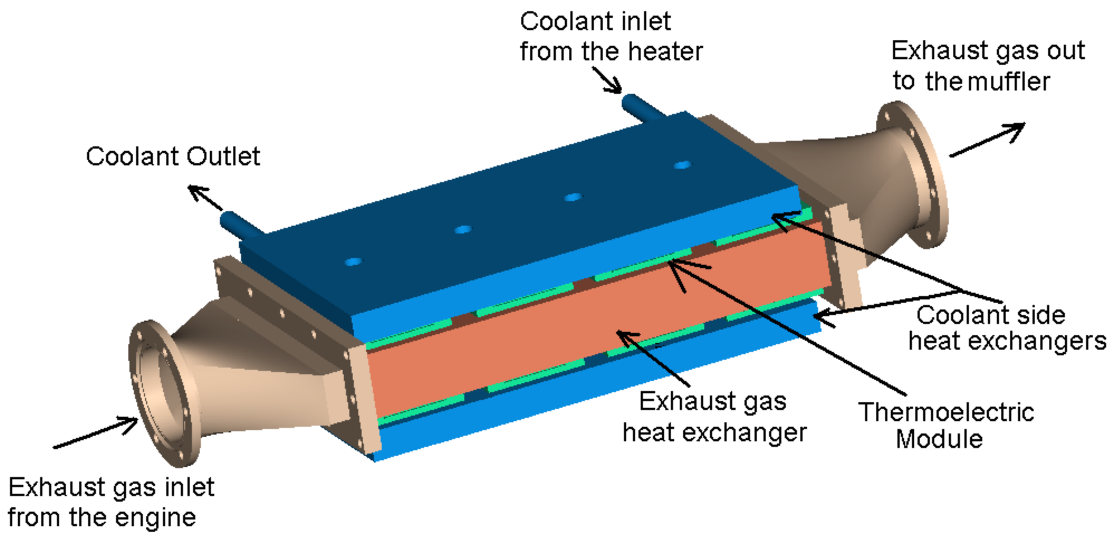


Fig.5 Thermoelectric generator shown without case.

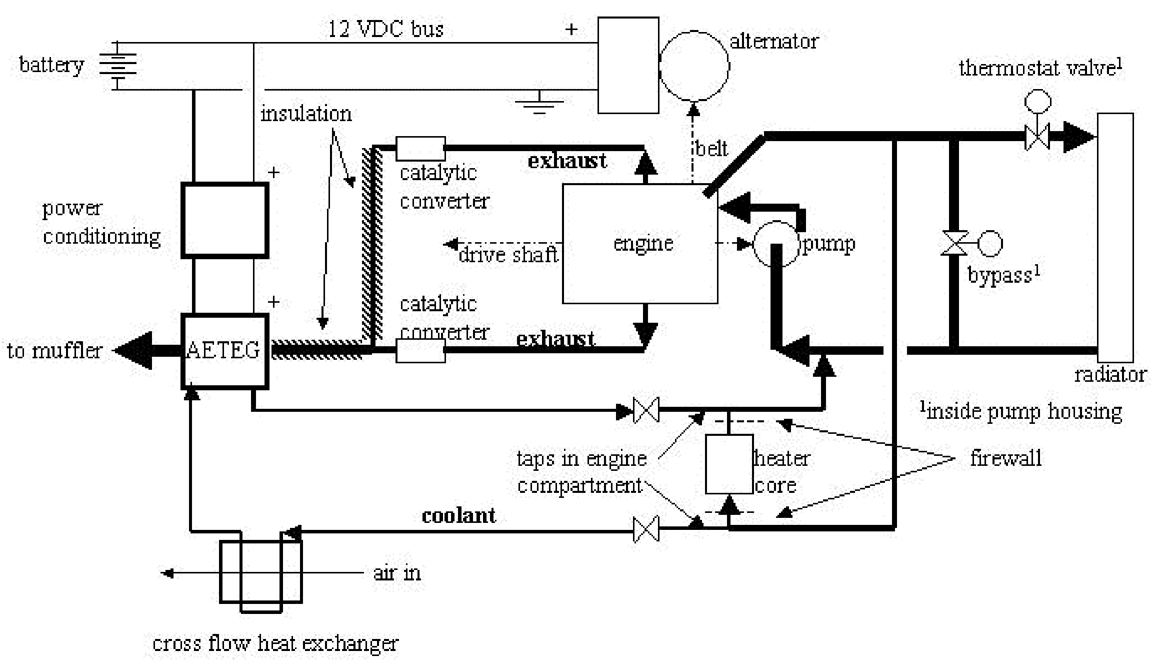


Fig.6 Automotive exhaust TEG (AETEG) system schematic.

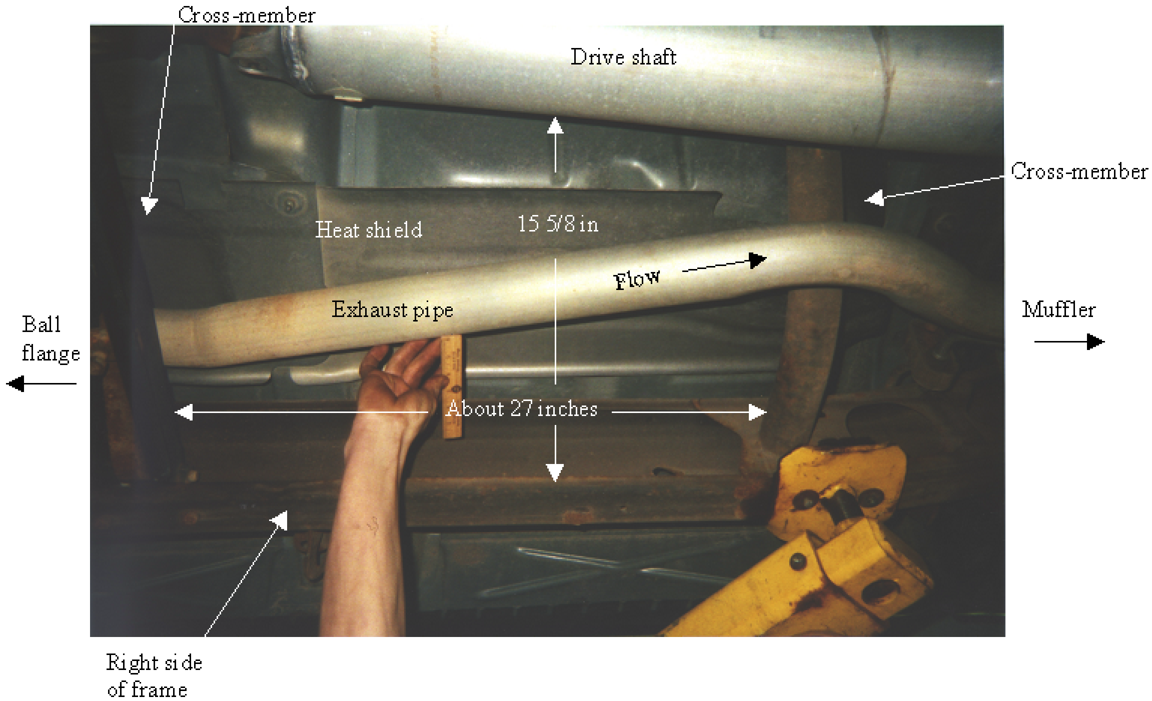


Fig.7 AETEG location.

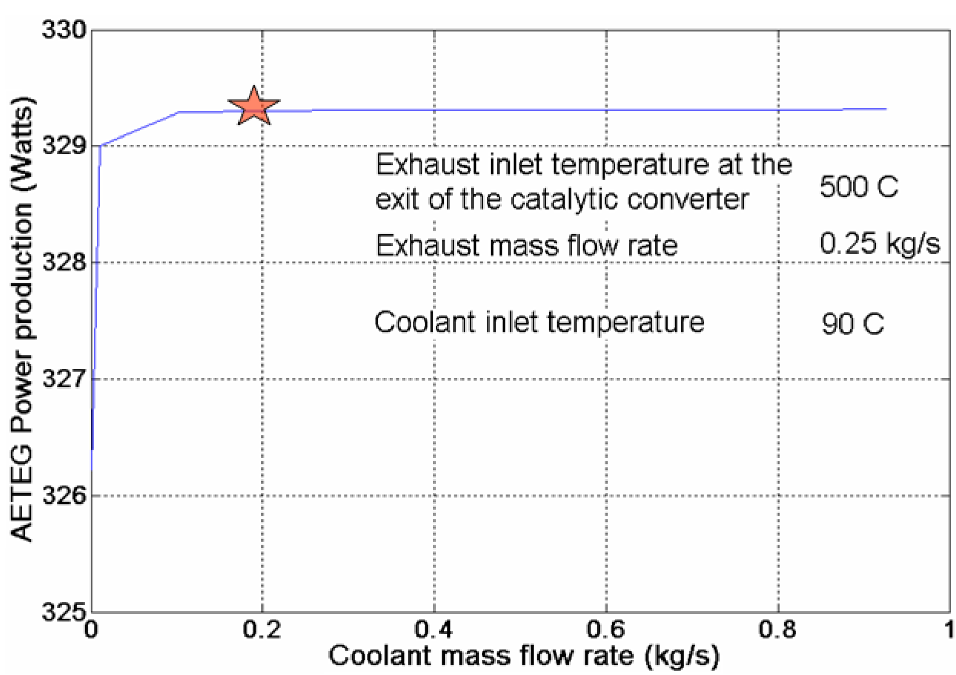


Fig.8 Sensitivity of power to coolant flow rate.

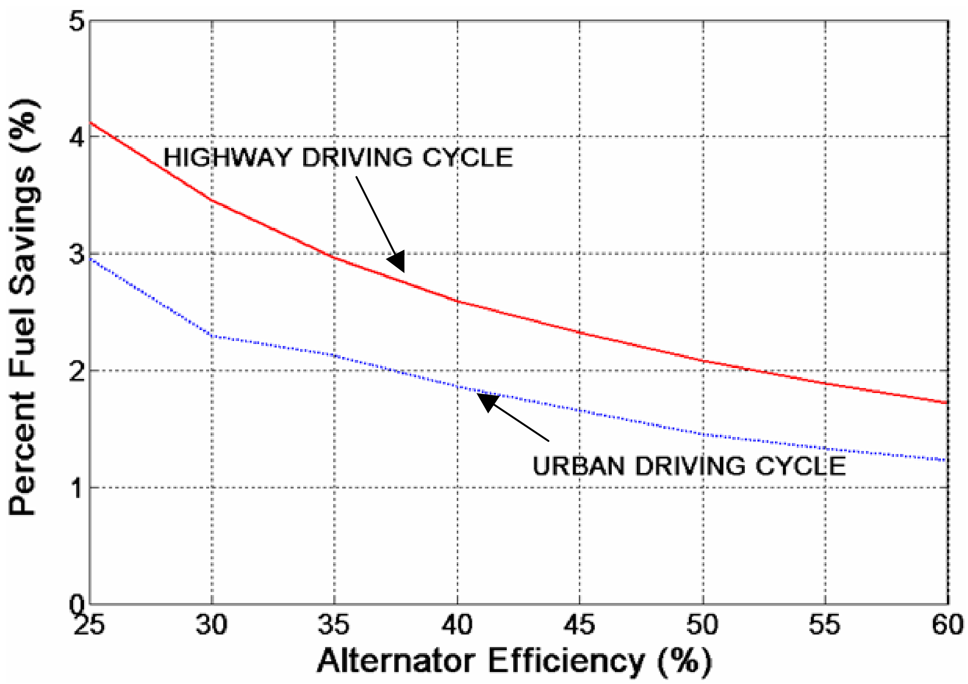


Fig.9 Percent fuel savings vs. alternator system efficiency.

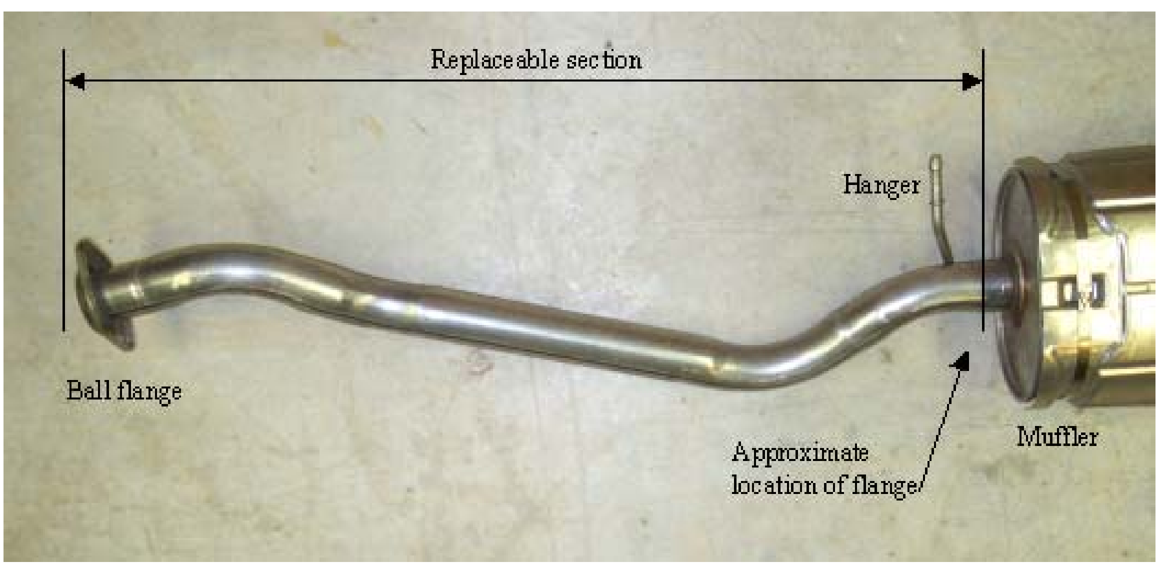


Fig.10 Replaceable section of exhaust pipe.

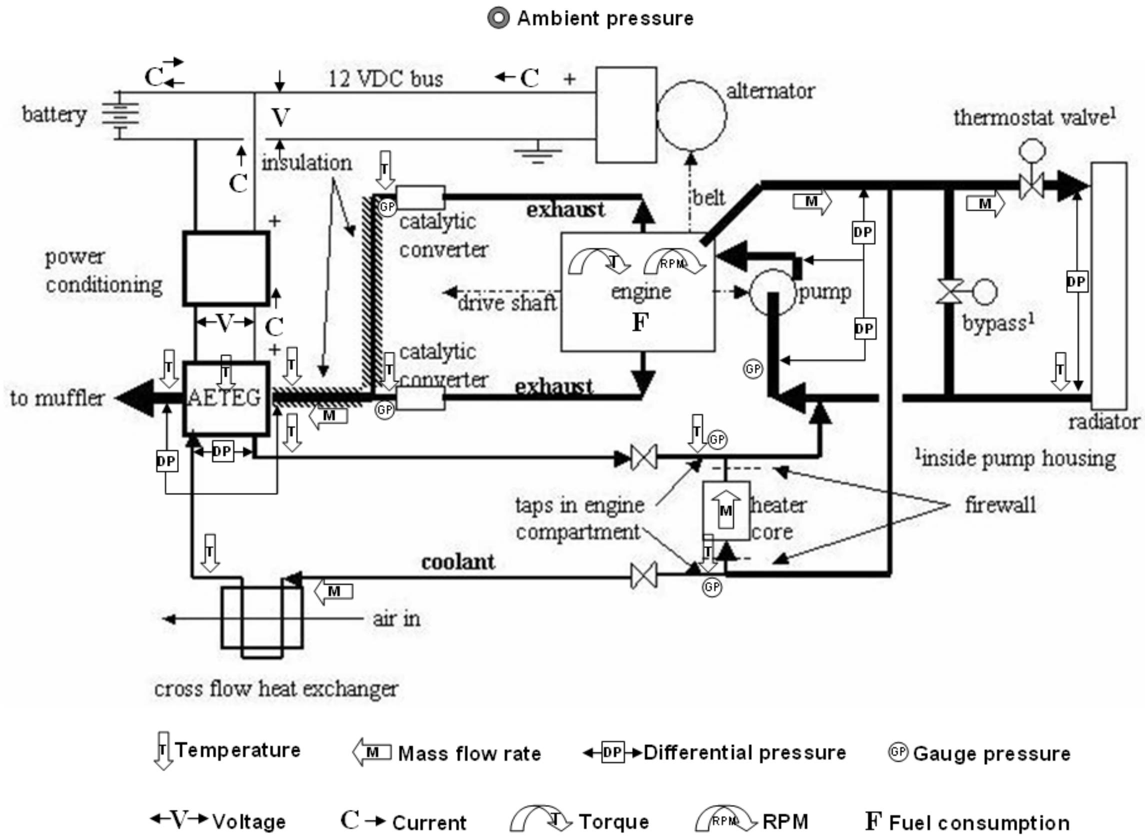


Fig.11 Measurements and experimental testing.

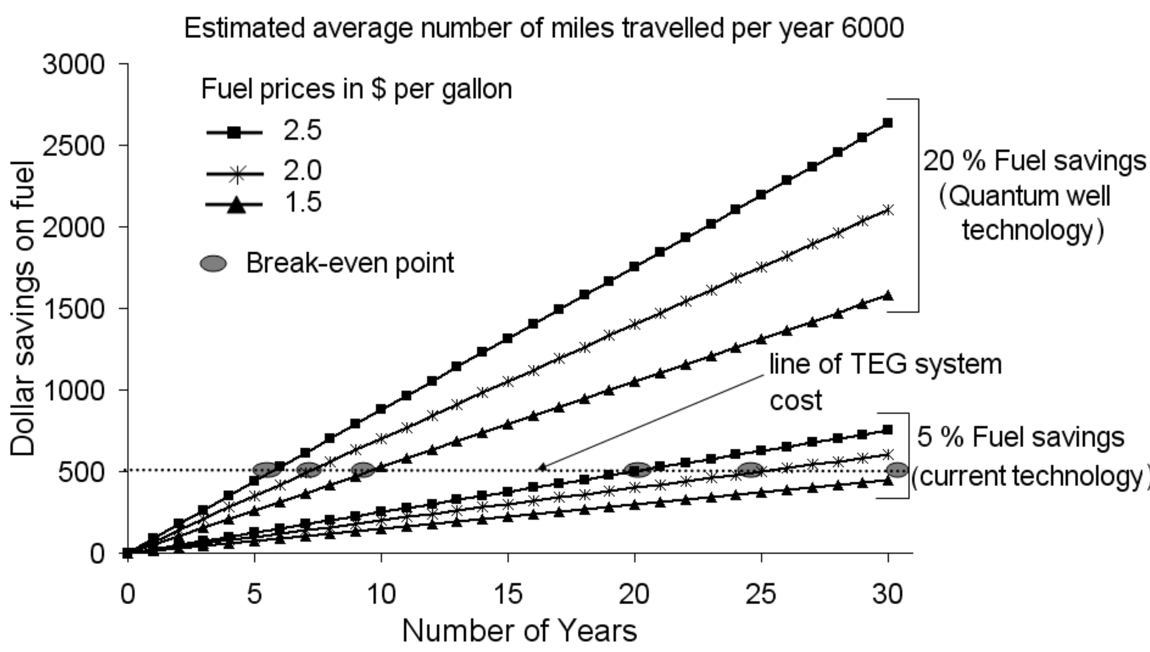


Fig.12 Dollar savings on fuel versus vehicle life for passenger cars.

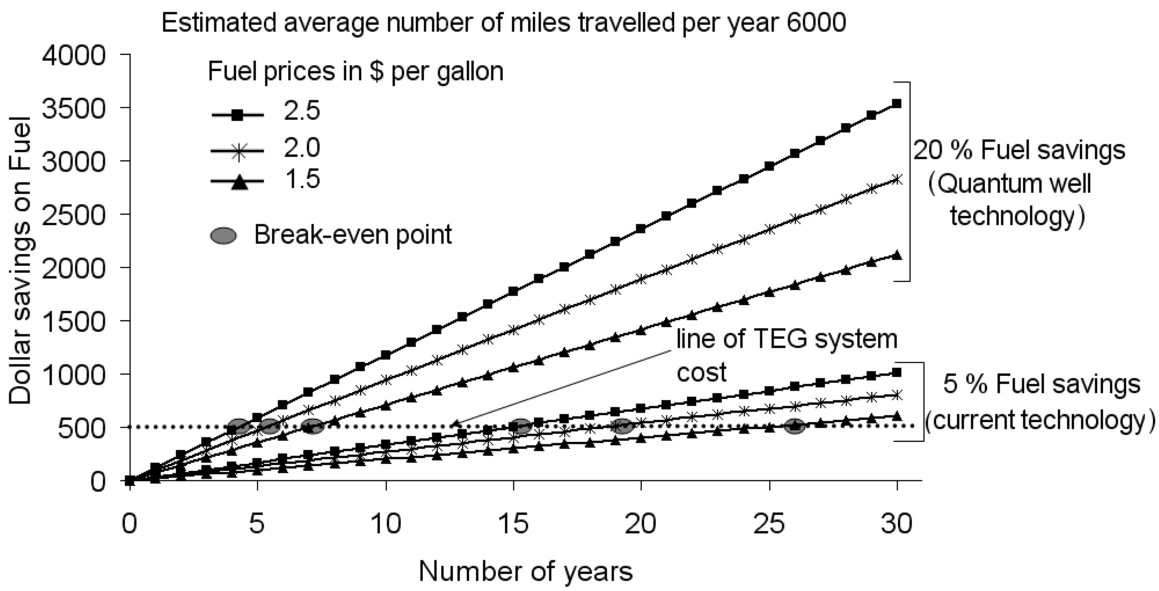


Fig.13 Dollar savings on fuel versus vehicle life for light trucks.

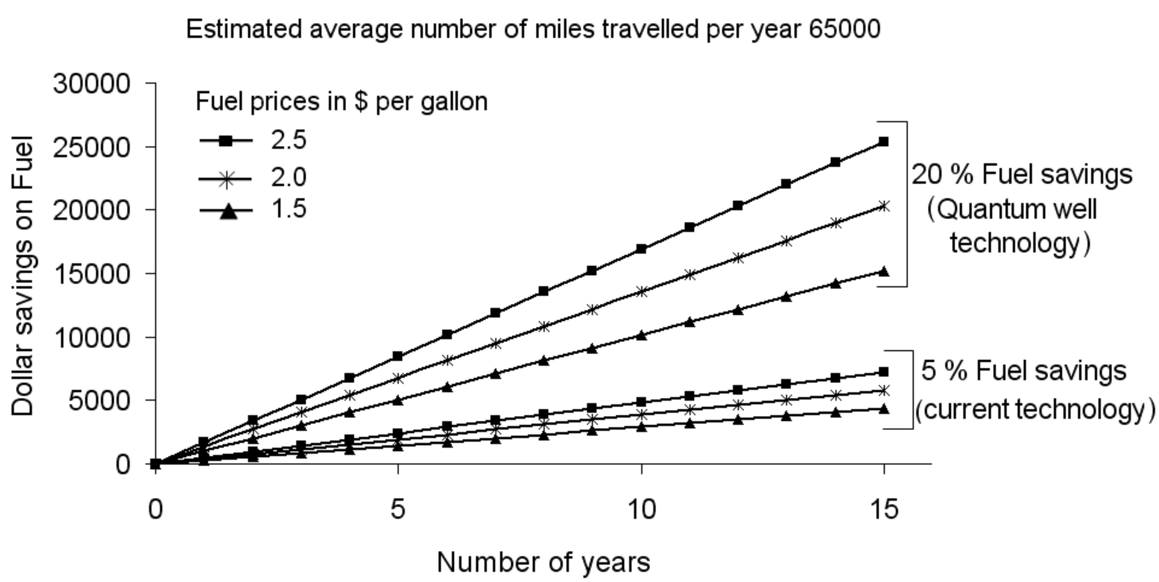


Fig.14 Dollar savings on fuel versus vehicle life for commercial fleets.