APPLICATION OF ADVANCED THERMOELECTRIC TECHNOLOGY TO THE DIESEL GENERATOR

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The auxiliary power requirements for heavy-duty trucks continue to increase. This will be particularly true when the power required to operate systems to reduce NO_x and particulates are introduced. If something is not done to reduce the engine auxiliary power load, these cleanup systems could essentially double the auxiliary power requirements which will result in a significant increase fuel consumption.

Hi-Z has been working for several years to develop a system that can reuse the waste energy available in the engine's exhaust to provide the auxiliary power for the truck[1]. The system we are currently testing is shown in Figure 1 mounted on a class 8 truck in place of the muffler. This generator uses thermoelectric modules made of bismuth-telluride to convert the exhaust heat directly to 1kW of electricity with an efficiency of about 5%. A study of replacing the alternator with a 1kW thermoelectric generator completed in 1992[2] showed that while the projected cost at the 1kW thermoelectric generator is more than a comparable alternator, the break even time for a class eight truck using such a system should be about two years in the United States and about eight months overseas.

This study only considered replacing the alternator. However, there are gains in fuel economy to be made if some of the other engine driven auxiliaries can be replaced by electric driven components whose power is derived from waste heat rather than from the engine shaft. These auxiliary devices could include the fan, power steering, power brakes, air compressor, NO_x and particulate cleanup systems, and possibly air conditioning.

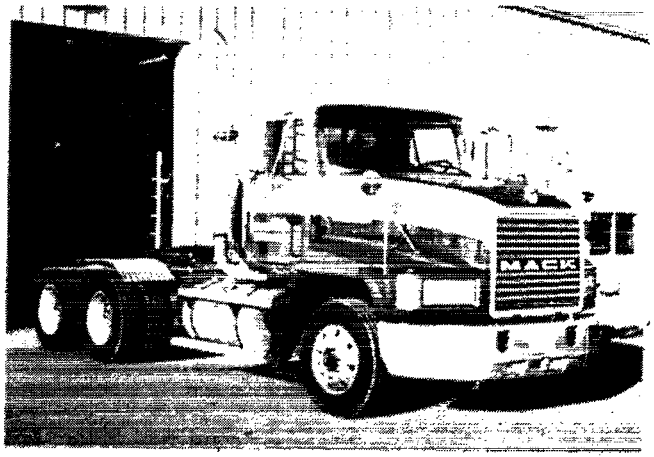

Figure 1: 1kW Thermoelectric Generator Installed on a Class 8 Truck

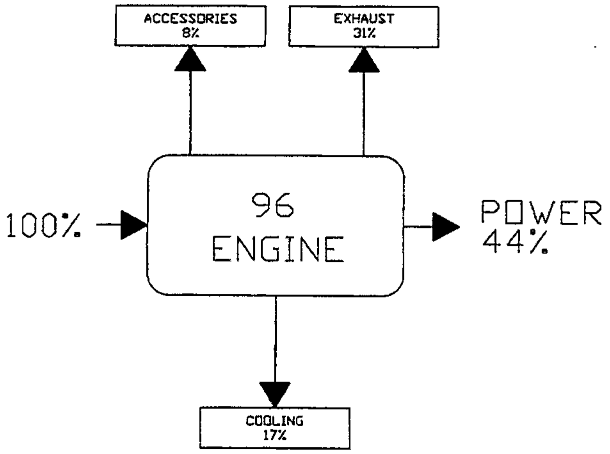

Figure 2: Energy Diagram for 96 Diesel Engine

Figure 2 is an energy diagram for a typical present-day (96) Diesel engine. Figure 3 shows the same engine with a 5% efficient thermoelectric generator. One sees that the efficiency of the engine is increased almost two percentage points or 4.4% using the thermoelectric generator.

One has two choices to reduce the breakeven times. The first is to reduce the cost of the

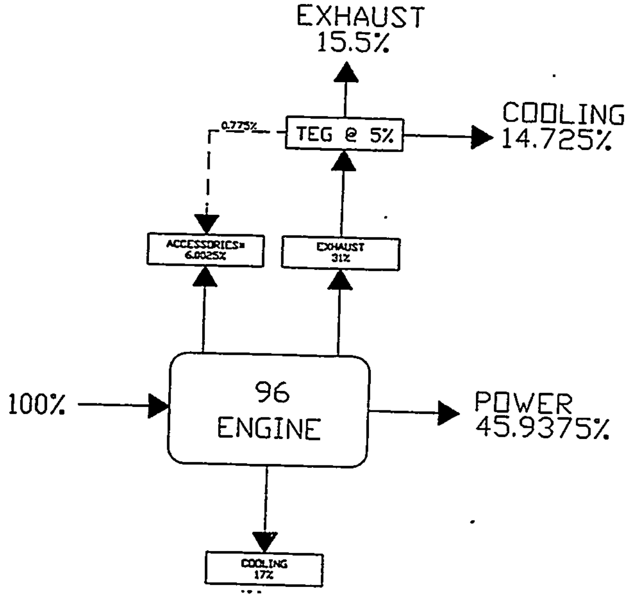

Figure 3: Energy Diagram for 96 Engine with 5% Thermoelectric Generator

generator components and the second is to increase the system conversion efficiency.

Reducing component cost is difficult to do by itself. It can be more easily achieved, however, when the conversion efficiency is increased because one needs to transfer and convert less energy to provide the same output power. This results in fewer, smaller, and, therefore, cheaper components being required which should result in a lower cost and, therefore, a shorter breakeven time.

Hi-Z is approaching the problem of increasing system efficiency in two ways. The first is a near term program which should bear fruit within the next few months and the second is a long term program which may require several years to complete.

NEAR TERM

The Jet Propulsion Laboratory in Pasadena recently announced[3] the development of zinc-antimonide (βZn_4Sb_3). The figure of merit (Z) for several conventional P-type thermoelectric materials including zinc-antimonide are shown as a function of temperature in Figure 4. One can see that the Z for zinc-antimonide is higher than that for bismuth telluride above about 125°C. Since the energy conversion is proportional to the area under the ZT curve, the use of a P-type thermoelectric element made of a combination of bismuth-telluride on the cold end and zinc-antimonide on the hot end holds promise for a higher, greater conversion efficiency than using P-type bismuth-telluride alone in the 250 to 300° C range.

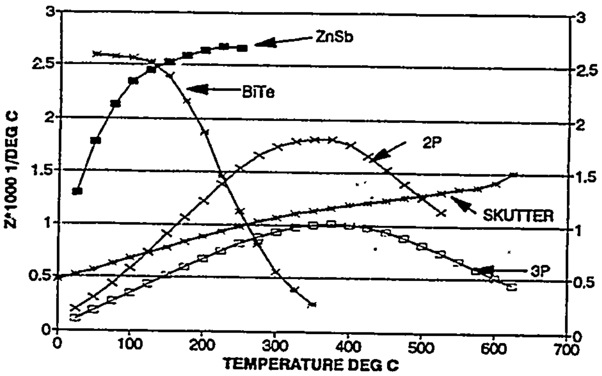

Figure 4: Figure of Merit Vs. Temperature for Several Thermoelectric Methods

Hi-Z and JPL are currently working on a program funded by DARPA to segment P-type zinc-antimonide and P-type bismuth-telluride to optimize the system conversion efficiency. If this program is successful, the module conversion efficiency will increase from 5% to about 7% which represents a 40% increase.

Figure 5 is an energy diagram for a conventional (96) engine with a 7% efficient thermoelectric generator showing where the energy goes in percentages. In this case the engine efficiency is increased by 2.7 percentage points or 6.16%.

LONG TERM

Hi-Z has been developing multilayer quantum well (MLQW) thermoelectrics for several years. These materials consist of very thin (100Å) alternating layers of materials with two different electron band gaps. When properly fabricated, the resulting material has very much improved thermoelectric properties compared to the same basic material made by conventional bulk methods.

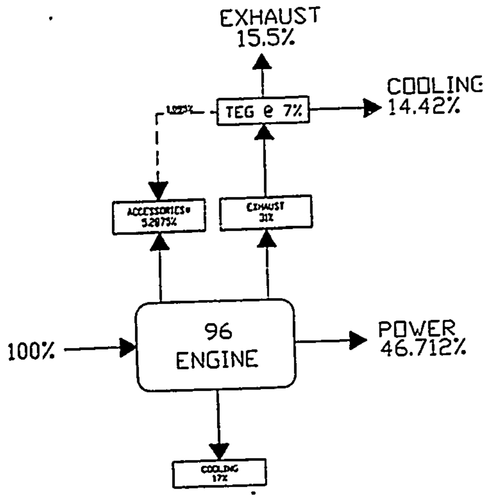

Figure 5: Energy Diagram for 96 Engine with 7% Thermoelectric Generator

Two types of MLQW systems have been discovered to date and both are now being developed under contracts to DoE. These systems are the silicon-germanium MLQW[4] and the boron carbon MLQW[5]. The silicon-germanium MLQW data indicate they will be used for cooling applications while boron carbon MLQW indicate they are good for power production. The boron carbon MLQW will be discussed first.

One of the problems that remain to be solved with the boron-carbon MLQW is that it can only be made as a P-type material. We are currently investigating other materials systems to see if we can develop an N-type MLQW material with high temperature capability similar to that of the boron-carbon MLQW.

A conventional N-type bulk alloy such as bismuth-telluride can be used with the P-type boron-carbon MLQW materials to form the required couples. This will not result in conversion efficiencies as high as a system which uses both N- and P-type MLQW, however, the theoretical conversion efficiencies are still significantly higher than those provided by a system which uses only conventional bulk alloys. The current estimate is that a thermoelectric conversion system which uses a boron-carbon MLQW for the P legs and conventional bismuth-telluride for the N leg will have a conversion efficiency of about 20%.

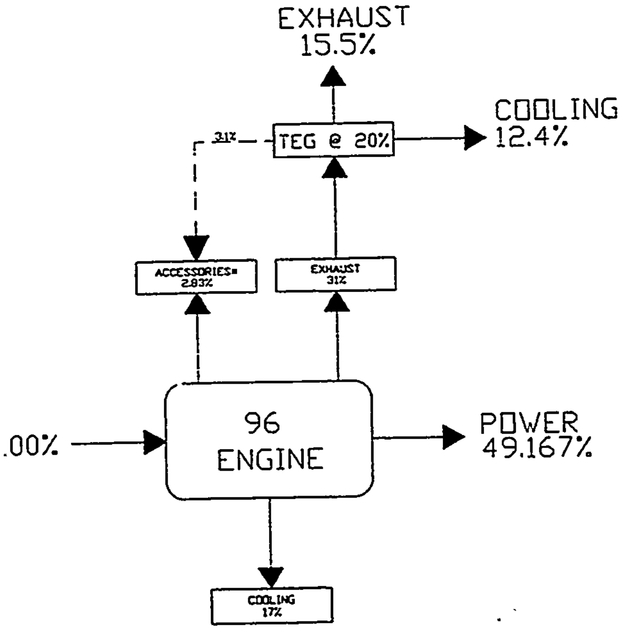

Figure 6: Energy Diagram of 96 Engine with 20% Thermoelectric Generator

The energy balance diagram shown in Figure 6 is for a present day (96) engine and a thermoelectric generator with a 20% energy conversion efficiency which can be achieved using the MLQW technology. In this case the overall energy efficiency is improved by a little over 5 percentage points or 11.1% compared to the standard engine.

Figure 7 shows the energy diagram for a conventional LE 55 engine. Since there is less energy content in the exhaust of the LE 55 than the present day (96) engine, less energy is available for conversion. However, the inclusion of a thermoelectric generator with 20% efficiency would still improve the efficiency of the LE 55 by over 3 percentage points or 6%, as shown in Figure 8.

It appears possible that the conversion efficiency of a MLQW device could be as high as 40% if a high temperature N-type material can be identified. If that does happen, then the energy balance for the LE 55 with an advanced thermoelectric generator could be as shown in Figure 9. This energy balance shows a potential efficiency improvement of almost 8.5 percentage points or 15.4% over the LE 55's nominal 55 percent efficiency.

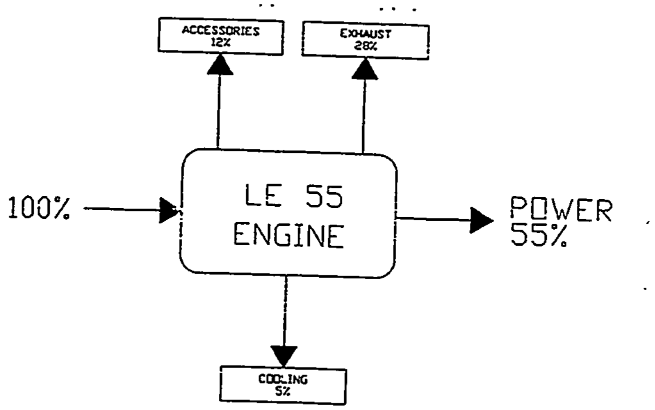

Figure 7: Energy Diagram of LE 55 Engine

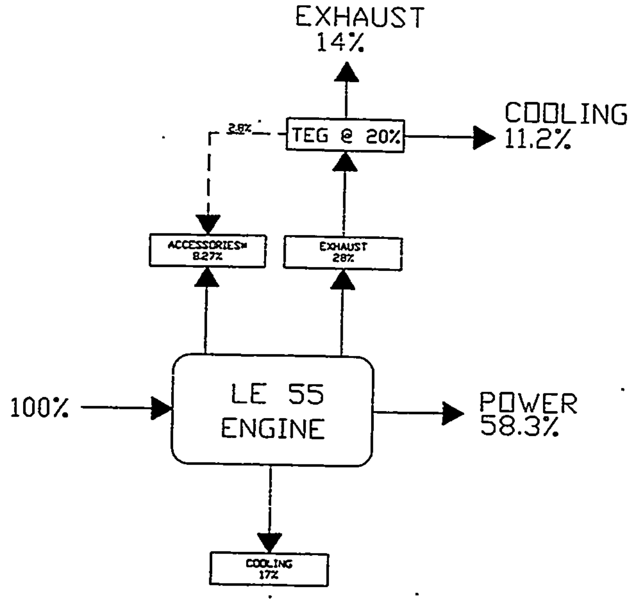

Figure 8: Energy Diagram of LE 55 Engine with 20% Thermoelectric Generator

CONCLUSION

The overall engine efficiency of large Diesel engines can be improved by adding a thermoelectric generator to convert some of the energy available in the exhaust to useful electric energy. The overall percentage improvements which can be expected from current materials is low. However, new materials are being developed which can lead to significant improvements in overall engine efficiency over the next several years. Some of these materials will be available within a few months while more advanced materials

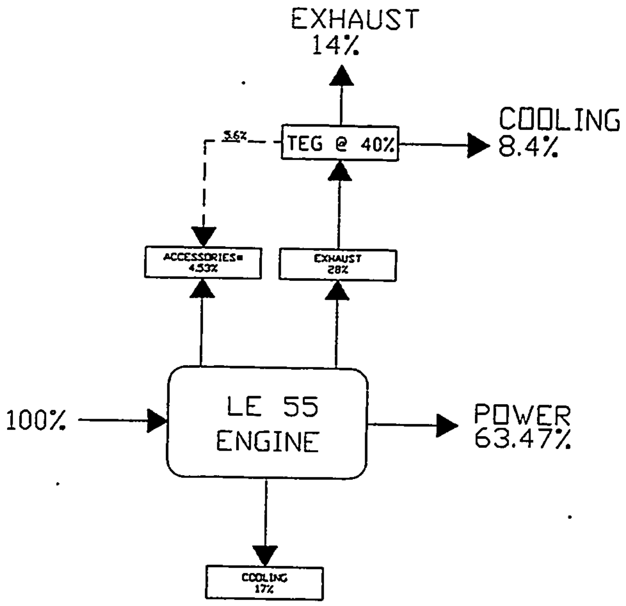

Figure 9: Energy Diagram of LE 55 Engine with 40% Thermoelectric Generator

will require several years of development. Incorporation of these new thermoelectric materials should lead to a significant improvement in overall engine efficiency as well as a shorter break-even time. While the improvements expected are greater when thermoelectrics are applied to present day engines, it will also significantly improve the efficiency of the advanced LE 55 engine.

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