Thermoelectric Development at Hi-Z Technology

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Abstract

An improved Thermoelectric Generator (TEG) for the Heavy Duty Class Eight Diesel Trucks is under development at Hi-Z Technology. The current TEG is equipped with the improved HZ-14 Thermoelectric module, which features better mechanical properties as well as higher electric power output. Also, the modules are held in place more securely.

The TEG is comprised of 72 TE modules, which are capable of producing 1kW of electrical power at 30 V DC during nominal engine operation. Currently the upgraded generator has completed testing in a test cell and starting from August 2001 will be tested on a Diesel truck under typical road and environmental conditions. It is expected that the TEG will be able to supplement the existing shaft driven alternator, resulting in significant fuel saving, generating additional power required by the truck's accessories.

The electronic and thermal properties of bulk materials are altered when they are incorporated into quantum wells. Two-dimensional quantum wells have been synthesized by alternating layers of B_4C and B_9C in one system and alternating layers of Si and $Si_{0.8}Ge_{0.2}$ in another system. Such nanostructures are being investigated as candidate thermoelectric materials with high figures of merit (Z). The predicted enhancement is attributed to the confined motion of charge carriers and phonons in the two dimensions and separating them from the ion scattering centers.

Multilayer quantum well materials development continues with the fabrication of thicker films, evaluation of various substrates to minimize bypass heat loss, and bonding techniques to minimize high contact resistance. Quantum well thermoelectric devices with N-type $Si/Si_{0.8}Ge_{0.2}$ and P-type B_4C/B_9C have been fabricated from these films. The test results generated continue to indicate that much higher thermoelectric efficiencies can be achieved in the quantum wells compared to the bulk materials.

Background

The current Diesel truck TEG project started late 2000 as a four-year effort funded by the U. S. Department of Energy (DOE). The major goal is to design, fabricate and road test 1 to 3 kW TEG for Class 8 Heavy Diesel Trucks. Previous efforts(1) demonstrated the feasibility of 1kW TEG but experienced some mechanical problems during the road test(2). An improved thermo-electric module (TEM), the HZ-14, was utilized for this project.

These modules are manufactured by the patented technology to replace the original HZ-13 TEM enables large-scale automated production with its associated reduction of the production cost. The HZ-14 contains 49 bismuth-telluride couples electrically separated by a special frame called an "eggcrate". The eggcrate is manufactured by an injection molding process that makes the TEM fabrication less expensive. The eggcrate and a completed HZ-14 module are presented in Figure 1.

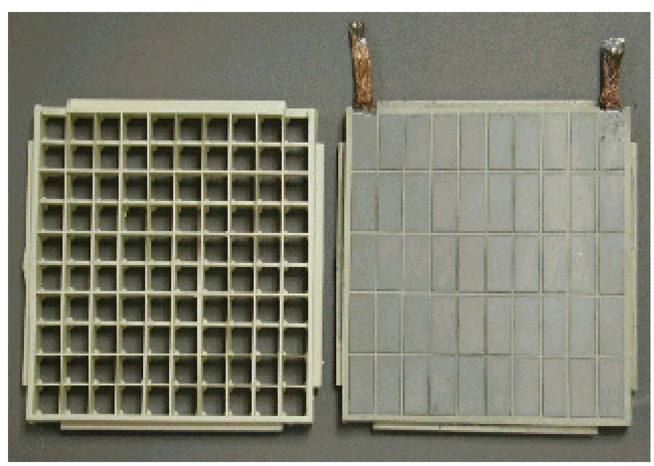

Figure 1. Eggcrate and HZ-14 thermoelectric module

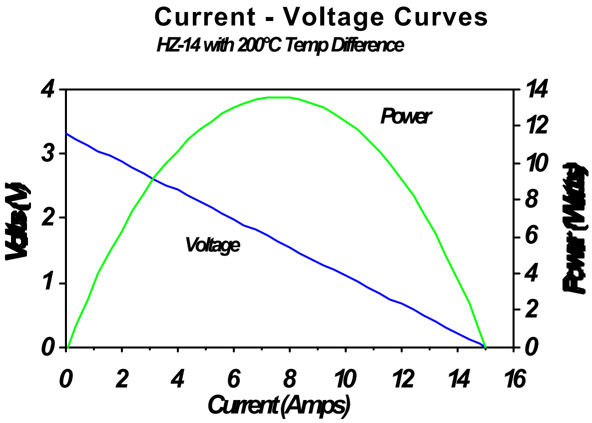

Figure 2. ÄT vs. Open Circuit Voltage

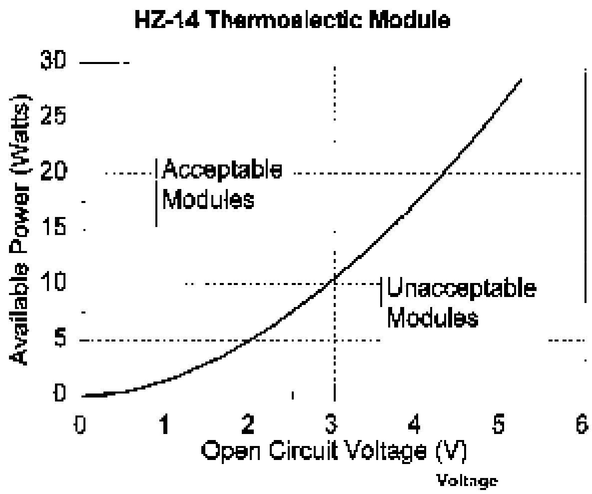

Figure 3. Power vs. Open Circuit Voltage

A set of 72 TEM (8 arrays with 9 module in each array) was selected for this project by performance and thickness. The TEM thickness variation for each array was less than 0.001" to ensure uniform compression of the modules.

In order to prevent TEM lateral movement aluminum strips (0.032" thick) were epoxy bonded to the heat sinks on each side of the module. In addition, RTV was applied to the heat sink at the TEM corner.

A new high temperature thermally conductive grease was formulated and tested at Hi-Z. It has demonstrated superior performance at the TEM hot side operating temperature (about 250 - 275°C) and was selected for the TEG assembling.

TEG Hot Air Test

Prior to in-cell testing, the TEG was tested at Hi-Z with the hot air blower that simulated Diesel engine exhaust. The hot air blower (with integrated heater) is capable of supplying about 165 cfm of air heated up to 500°C. This test was conducted in order to check the general functionality of the TEG and major subsystems such as electrical (array interconnection, bus bars, terminals), cooling system and measurement system.

Two loading devices were designed and fabricated. The first one - electronic loading device (ELD) allows for fine-tuning the load and to setting the optimal voltage/current conditions. The ELD is shown in Figure 4. The second loading device is comprised of six car headlights, interconnected in parallel/series way to match the TEG resistance.

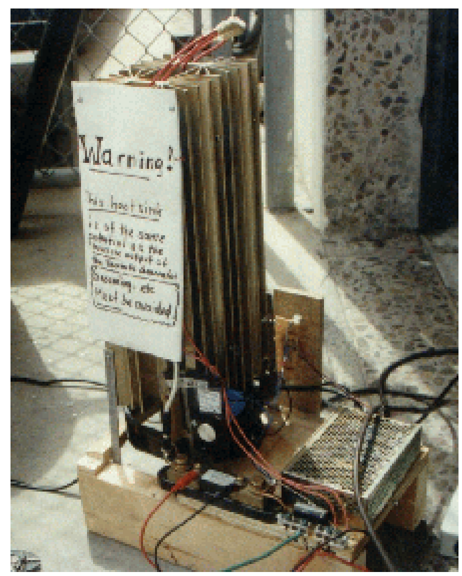

Figure 4. Electronic Loading Device

The TEG is equipped with the 12 thermocouples that measure the temperatures at different places the generator, such as hot and cold side of the TEMs, temperatures on the face of the heat exchanger and heat sinks.

One array of the TEMs (heat sink #1) has special wiring that allows measuring open circuit voltage and voltage under loading from individual modules. These measurements indicate how uniform is the temperature differential profile and the amount of power produced in different sections of the generator.

Figure 5 illustrates the TEG test setup with the hot air blower and car light bulbs loading device.

Figure 5. Hot air blower TEG test setup with car light bulbs load

In-Cell TEG Test

The in-cell generator test was conducted with Cummins 335 Diesel engine. The experimental test setup is shown in Figure 6.

During this test the engine loading was changed from 75 to 290 horse power (HP), the engine speed ranged from 1300 to 2100 RPM. The exhaust flow rate at 2100 RPM, 335 HP and 627°C exhaust temperature estimated of 2500 CFM.

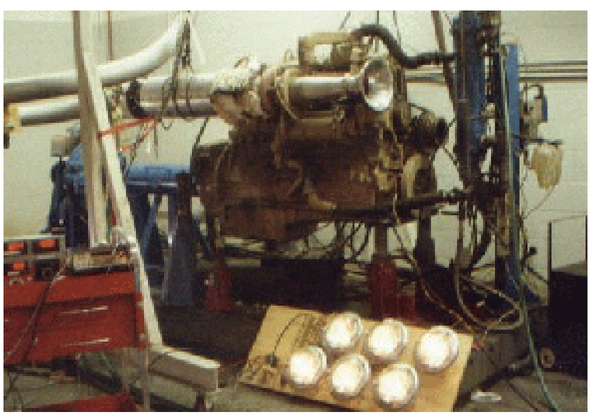

Figure 6. 1 kW TEG in-cell test. ELD and light bulb load operate simultaneously

It was found that TEG power output strongly depended on engine loading and less on the engine speed as illustrated in Figure 7 and in agreement with the data reported by Bass(2). The highest electric power output from the TEG (over

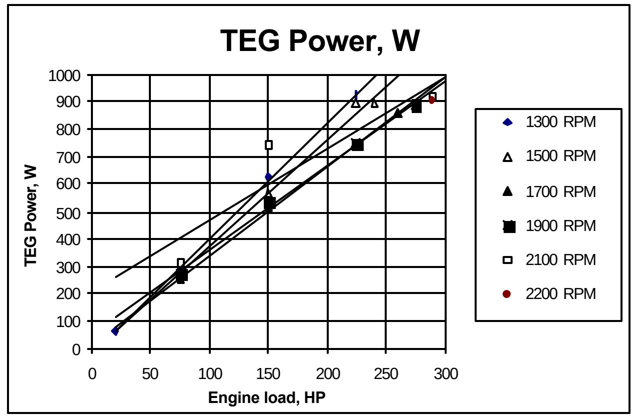

Figure 7. TEG power output as a function of the engine load and speed

900W) was recorded at engine load close to 300HP. The test engine could not reach its design output which limited power produced by TEG.

The next test of the generator is scheduled to start in August as a joint effort with our industrial partner, Paccar. The test is planned to be conducted on a truck equipped with the Cummins 550 HP engine. The TEG performance will be evaluated at different driving conditions. In addition, the resistance to shock and vibration will be investigated.

Evaluating the results in-cell and road driving test results, a new generation of the TEG will be designed, fabricated and tested 2002.

Self-Powered Preheater

Another automotive industry product that utilizes Hi-Z thermoelectric modules is under development by OmniNove, Sweden. This product is a self-powered preheater presented in Figure 8.

This preheater burns Diesel with the rate of 0.8 l/hr. Inlet water temperature is 65EC, output is 80EC. Thermal power output is 6.3 kW and it produces 95-100 W of electric power generated by eight HZ-20 modules.

Electric power consumption of the complete preheater system including a water pump is 35 W, so the excess electric power can be used for recharging battery or other truck electric needs. Omni Nova plans to introduce this self-powered preheater as a commercial product within the next year.

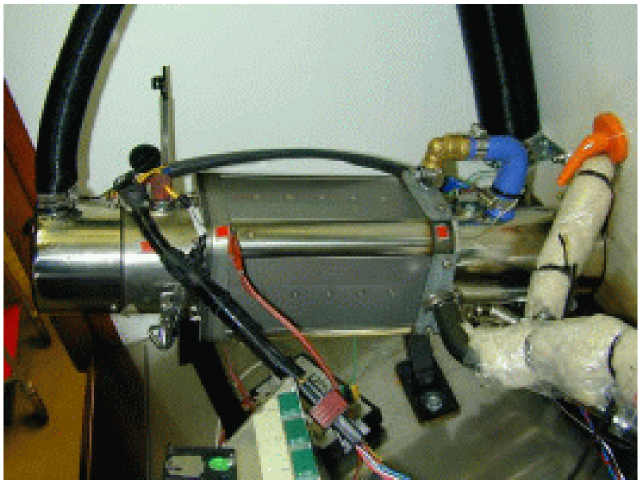

Figure 8. Self Powered Fluid Heater

Advanced TEG system potentials

The current TEG is comprised of 72 HZ-14 modules. Each module is capable of generating 14 W electricity at the designed temperature differential (ÄT = 200EC). Practically, 1 kW is the maximum power that could be generated by such a unit. However, the exhaust from the TEG still contains considerable energy (exhaust temperature observed during the in-cell testing was above 400EC at maximum power generating conditions). One way to convert more exhaust heat into electricity is to scale up the TEG or to install several 1 kW units into the truck exhaust system. The other option is to utilize more effective quantum well thermoelectric materials that are capable of increasing the TEG efficiency by a factor of four.

Hi-Z is currently developing Quantum Well thermoelectric materials that could make a major breakthrough in thermoelectric technology.

Experimental Results for QW Thermoelectric

The theory of the Quantum Well materials, properties and some preliminary development results are presented in Reference 4. Hi-Z has deposited B_4C/B_9C and Si/SiGe multilayer films by sputtering, to fabricate p-n couples from relatively thick multilayer films, and to measure performance of these couples as power generators.

The results, confirmed by NRL for B_4C/B_9C, indicate multilayer films could exhibit conversion efficiencies as high as 22-24% compared to bulk materials showing 5% conversion efficiencies.

Film deposition for the multi-layer films was performed using a Veeco magnetron sputtering unit at Hi-Z, with 3-inch targets. Techniques were developed to control and measure the thickness of each layer, with a typical target of 100D per layer, deposited in about 1 minute. Deposition normally occurred on a +100, silicon wafer 3 inches in diameter. Some non-uniformity was noted around the edges of the wafer, so samples for measurement were taken from the central area. In the case of the B_4C/B_9C multilayer films, annealing was performed prior to measurement.

It was previously found that the Si/SiGe multilayer films show superior performance only at room temperature and below, but their performance at temperatures up to 250EC was comparable with that of bulk bismuth telluride. Couples were therefore fabricated using B_4C/B_9C multilayer films for the P-leg, and either Si/SiGe multilayer films or bulk bismuth telluride for the N-leg.

Table 1 gives a summary of the in-plane data on p-n film thermocouples. It may be noted that data were obtained on up to four couples. Table 1 shows the consistency of the measurements on the various couples, and illustrates the magnitude of the advance made possible by the multilayer film technology, versus the best comparable performance with bulk materials.

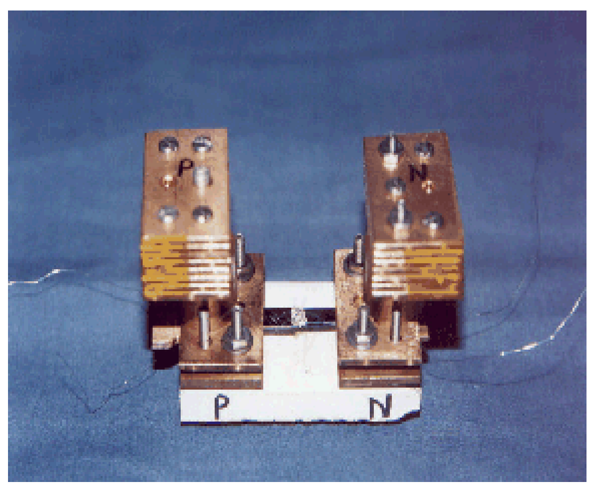

Figure 9. Test fixture used for measure-ment of the power of multilayer film couples. The heat source was located centrally with cold junctions on either side.

Table 1
Thermoelectric Performance of B_4C/B_9C films with either Si/SiGe Films or Bulk Bi_2Te_3 Based Alloys

Films on ~5µm Si substrate	Film Thickness	Voltage & Resistance Measured Power (µW) **EXPERIMENTAL 40°C to 90°C**	Loss of Efficiency Due to Si Substrate (%)	Calculated Efficiency (%) T_{cold} . 50°C and T_{hot} . 250°C **THEORETICAL**
B_4C/B_9C-Si/SiGe P-N couple	1µm	0.125	>90	**<2**
B_4C/B_9C-Si/SiGe P-N couple	**11µm (0.433 mil)**	**0.126****	**35**	**~20**
Bulk Bi_2Te_3 Couple	NA	0.01*, Hi-Z module	NA	~5, Hi-Z Module
Bulk SiGe Couple	NA	0.02*	NA	<1
Bulk B_9C-SiGe Couple	NA	0.004*	NA	<1

*Published data
**Normalized to 1 Fm thickness

Table 2
Comparison of Hi-Z and NRL data on composites measured at the two locations. The NRL measurements confirm the exceptionally high á²/ñ values measured at Hi-Z

	Quantities	**NRL**	**Hi-Z**	Bi_2Te_3 [iv]
Composite: (B_4C/B_9C films on Si substrate)	$ñ_c$ (mÙ-cm)	30 [i]	35	0.71
	$á_c$ (µV/°C)	860 [i]	900	200
Film	$ñ_f$ (mÙ-cm)	0.6 [ii]	0.7	NA
	$á_f$ (µV/°C)	1050 [ii]	1100	NA
Power Factor Number of Films	$á^2/ñ$ (µW/cm-°C)	459 [ii]	432	56
Figure of Merit of films	$Z_{Bulk\ thermal\ k}$ (1/°C)	9.2×10^{-3} [ii]	9×10^{-3}	3.4×10^{-3}
	$Z_{QW\ thermal\ k}$ (1/°C)	27.6×10^{-3} [iii]	27×10^{-3}	NA

i. Measured at NRL (Naval Research Laboratory)
ii. Calculated based on known substrate and film thickness, and substrate á and ó.
iii. Based on recent thermal conductivity measurements at UCLA.
iv. Best values of Bi_2Te_3 alloys are shown.

Table 3
The Thermoelectric Performance of the Composite (Z_c) Increases as the Thickness of the Si Substrate Decreases

Si Substrate thickness (mm)	0.5	0.25	0.05*	0.005 = 5 µm*
ñ$_c$ (mÙ-cm)	30	15	3.6	0.63
á$_c$ (µV/°C)	860	860	860	860
Z_c á^2/ñ (1/°C) Bulk thermal k of B-C	0.3 x 10^{-3}	0.6 x 10^{-3}	4 x 10^{-3}	8 x 10^{-3}
Z_c á^2/ñ (1/°C) Recent UCLA thermal k	0.5 x 10^{-3}	1 x 10^{-3}	9 x 10^{-3}	25 x 10^{-3}

*Available commercially.

The measurements in Table 1 were made using the arrangement shown in Figure 9. A multilayer film on a silicon substrate was mounted between a heat source at 90EC and a cold junction at 40EC. The output power for the 11 Fm film shown in Table 1 has been normalized to 1 Fm for easier comparison the other values. The actual measured output of the 11 Fm couple was 1.38 Fm .The measured data were processed to subtract the effects of the substrate, using known parameters for the silicon. The data have been very rewarding and indicate that the 20% efficient device may be attainable.

The data show extraordinary promise for thermoelectric couples based on multilayer B_4C/B_9C films. The power delivered into a matched load, at the level of a fraction of a microwatt, appears small, but is produced from a very small amount of active material. The efficiency calculated for each couple depends on the value taken for the thermal conductivity. If we assume no reduction of the thermal conductivity, i.e. use the higher value for bulk B_4C/B_9C, the efficiency is about 4% for the lower temperature (90EC) heat source and 10-11% for the 250^{o}C source. These figures are already a significant improvement over bismuth telluride and improve with the recent thermal conductivity measurements of UCLA as discussed below. Their power factor numbers (á^2/ñ) indicate that there is some quantum well confinement in the B_4C/B_9C films, as had been anticipated. The data of Table 2 have also been confirmed by measurements at the Naval Research Laboratory. This comparison is made in Table 2, which shows that the NRL and Hi-Z data are the same within a small experimental error.

The Seebeck coefficient does not change with the relative thickness of the Si substrate since this parameter is independent of thickness. However, as the Si substrate thickness is reduced, the ratio of the film resistance to the substrate resistance is increasing. Since the resistance of the film is so much lower than the Si substrate, the composite resistivity will drop as the substrate thickness decreases. Hi-Z is striving to use as thin as substrate as possible, such as the 5Fm (micron) Si that is commercially available.

Recent measurements at UCLA show that the thermal conductivity of the B_4C/B_9C multilayer films is significantly reduced in comparison with the bulk value (see Figure 15). Only a single measurement has been made, so this result should be regarded as tentative, but use of the UCLA value for the thermal conductivity leads to a factor of 3 enhancement in the performance of the material. The data based on the assumption of the UCLA thermal conductivity value are also included in Table 3 and Figure 10 and show the promise of this technology.

Table 3 shows the importance of maximizing the ratio of film thickness to substrate thickness. The substrate is a bypass heat loss and its thickness needs to be minimized. Flexible Si foil as thin as 5 micron thick is commercially available from Virginia Semiconductor. An efficiency of 22% using commercial Bi_2Te_3 or Si/SiGe as the N-leg is an improvement of over a factor of 4 in comparison with the best performance from a bismuth telluride p-n couple, and a sufficient improvement to justify a major expansion of thermoelectric

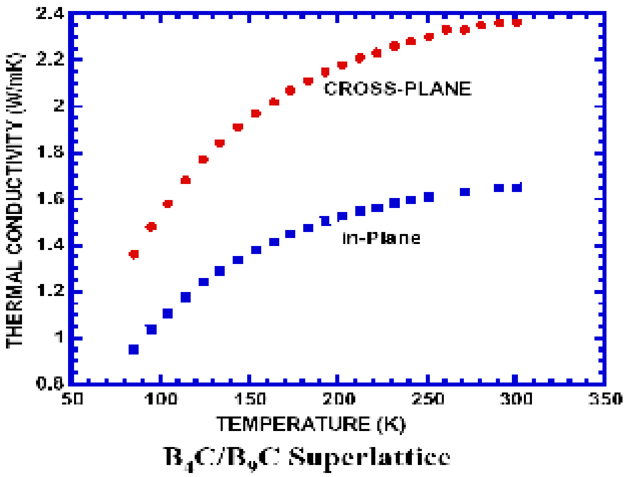

Figure 10. Thermal conductivity of B_4C/B_9C multilayer film, measured in-plane and cross-plane at UCLA. The in-plane conductivity is about1/3of the bulk value and is the value used in calculating the figure of merit (Z).

power generation when translated into working devices.

Future Goals

Our goal for an actual device is an efficiency of 20%, and we have demonstrated with the 5 Fm thick Si sample that this is an attainable target since our evidence suggests that this performance is feasible on a small laboratory scale. Scale-up to achieve similar performance in a useable device is therefore the clear goal for the future. Also, since cost is an important factor, it is encouraging that the 20% efficiency goal can be met by a couple in which the N-leg is bulk bismuth telluride or Si/SiGe QWs, the material used in current commercial production.

The replacement of the present 1 kW TEG unit by multilayer film materials with 20% efficiency would allow a reduction in fuel consumption between 12 and 30%, using a generator of 2 to 5 kW capacity. This performance would greatly reduce payback time and emissions, in addition to the fuel savings. The generation of additional power by use of a TEG allows emission control devices to be installed on the trucks at net decrease in fuel consumption. A 20% efficient thermoelectric generator could be adopted by truck manufacturers, who are already concerned with the limitations of the present output of alternators and are reluctant to increase alternator size. Figure 11 shows the energy flow diagram for a typical 96 diesel engine and the affect of adding both a conventional thermoelectric generator of 5% efficiency and a generator of 20% efficiency based on multilayer film materials are shown.

The comparison of the conventional (no TEG) design, with 5% and 20% TEG incorporated into the exhaust system is presented in Table 4. The comparison assumes that the truck will utilize the same amount of the electrical power supplied to the accessories and decrease the size of the alternator as TEG are incorporated.

Table 4 data clearly demonstrates the advantages of using a TEG in the truck exhaust system, specifically high efficiency Quantum Wells units. Conversely, the alternator size could be maintained and this additional power used for powering other devices such as a non thermal plasma or other emissions control devices.

Conclusions

1. Hi-Z Technology successfully developed and tested 1 kW TEG for Class 8 Diesel truck. Commercialization of the TEG will result in supplying additional power to the truck's electrical devices, substantial fuel saving and associated pollutant emission reduction.

2. Thermoelectric modules manufactured by Hi-Z are integrated into a TEG for both waste heat recovery system and engine preheaters.

3. Several compositions were investigated as a candidate for high efficiency Quantum Well thermoelectric materials. Experimentally, both B_4C/BeC and Si/SiGe indicated the feasibility of the 20% efficiency TEG devices.

Acknowledgments

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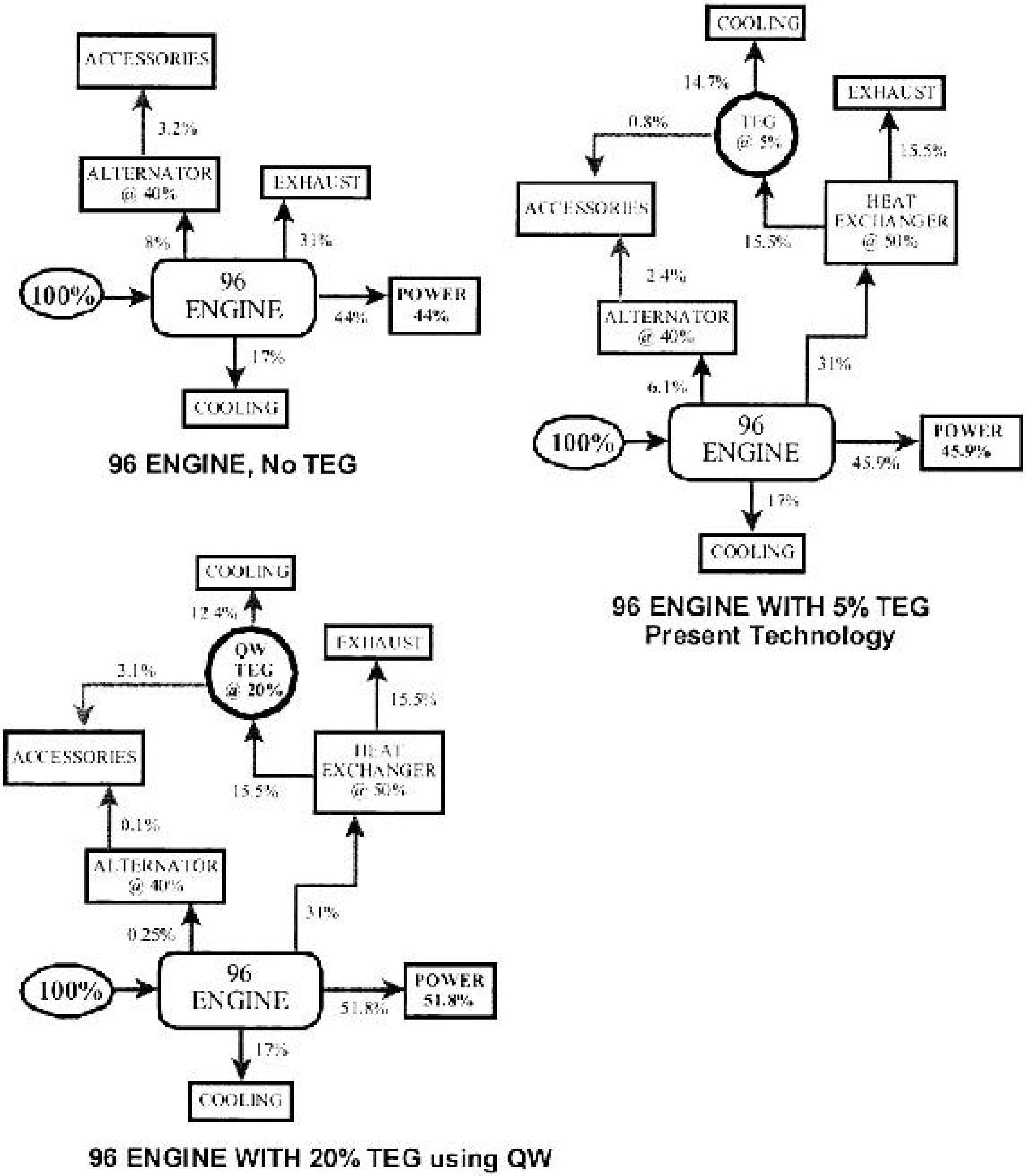

Figure 11. 96 Engine with several TEG options

Table 4

Energy Requirements for conventional and TEG/Diesel engine systems

System	Fuel Energy Input	Exhaust Energy	TEG Energy Input	TEG Energy Output	Alternator Capacity Required	Useful Power
No TEG	100%	31%	0	0	3.2%	44%
TEG, ç = 5%	100%	31%	15.5%	0.8%	2.4%	45.9%
TEG, ç = 20%	100%	31%	15.5%	3.1%	0.1%	51.8%

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