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TEG On-Vehicle Performance and Model Validation and What It Means for Further TEG Development

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A high-temperature thermoelectric generator (TEG) was recently integrated into two passenger vehicles: a BMW X6 and a Lincoln MKT. This effort was the culmination of a recently completed Department of Energy (DOE)-sponsored thermoelectric (TE) waste heat recovery program for vehicles (award #DE-FC26-04NT42279). During this 7-year program, several generations of thermoelectric generators were modeled, designed, built, and tested at the couple, engine, and full-device level, as well as being modeled and integrated at the vehicle level. In this paper, we summarize the history of the development efforts and results achieved during the project, which is a motivation for ongoing research in this field. Results are presented and discussed for bench, engine dynamometer, and on-vehicle tests conducted on the current-generation TEG. On the test bench, over 700 W of power was produced. Over 600 W was produced in on-vehicle tests. Both steady-state and transient models were validated against the measured performance of these TEGs. The success of this work has led to a follow-on DOE-sponsored TE waste heat recovery program for passenger vehicles focused on addressing key technical and business-related topics that are meant to enable TEGs to be considered as a viable automotive product in the future.

Key words: Thermoelectric, power generation, waste heat recovery, automotive

INTRODUCTION

In the fall of 2004, a team led by Amerigon (now Gentherm) began a Department of Energy (DOE)-sponsored program under DOE award #DE-FC26-04NT42279 to develop a thermoelectric generator (TEG) for passenger vehicles. Team members included BMW, Ford (added during phase 3), and Faurecia (added for phase 5). This program completed in the fall of 2011 with a high-temperature TEG integrated into two passenger vehicles: a BMW X6 and a Lincoln MKT. This paper summarizes the results of this program, with particular attention to the final phase results. The paper also discusses what is next for further TEG development.

PROGRAM HISTORY

In phase 1 of the program, the boundaries of the thermoelectric (TE) waste heat recovery problem were defined along with the system architecture. An initial model was created for the TEG, which was then utilized in a system model to provide an estimate for vehicle fuel economy improvement over a drive cycle.[1]

In phase 2, a small-scale high-temperature generator building block was designed and built. The goal for this building block was to use it to demonstrate TEG efficiencies >10% and, when multiple building blocks were linked together, produce power >20 W at temperatures >400°C. Further description of this development and results are discussed in previous papers.[2,3]

With limited availability of effective high-temperature materials in the size and shapes

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desired in time to complete phase 2, the team set out to build and test a full-scale generator using lower-temperature, more readily available, Bi_2Te_3 materials. Another goal of this build was to prove the effectiveness of the stack design for the TE engine. A liquid/liquid TEG was successfully built, producing over 500 W. Further description of this design and its results are described in Crane et al.[4]

In phase 3 of the program, the focus moved to building a gas/liquid generator with TE elements that could withstand temperatures up to 500°C and gas temperatures potentially over 600°C. Phase 3 had successes, including making over 100 W with a high-temperature, gas/liquid TEG made of segmented TE elements,[5] but it also had difficulties. With the flat-plate TEG design used in phase 2 and 3, it was difficult to keep the TE engines in good thermal contact with the hot and cold heat exchangers over large surface areas. Testing showed that some of the TE engines were in good thermal contact while others were not. It was difficult to apply sufficient pressure over the entire surface area of the TEG to maintain good thermal contact without crushing the TE engines in certain places.

In phase 4, the team embarked on a radical change to the TEG design. The design went from a flat plate to cylindrical design. The new cylindrical design could take advantage of the inherent thermal expansion in the device and allow the hot heat exchanger to expand into the hot shunts, eliminating any need for additional pressure being applied to the device. The cold shunt design changed as well, with the cold heat exchanger tubes being placed inside cold shunt sleeves. Again, no additional pressure was needed for thermal contact. A bypass was needed for the system to allow for excessive flows and temperatures to bypass the TEG, to avoid excessive backpressure for the engine, and to prevent overheating of the temperature-sensitive TEG components. In the new, cylindrical design, the bypass was placed inside the TEG, conserving precious system volume and allowing some additional power to be generated during bypass situations. A more complete description of the cylindrical TEG was reported previously.[6,7] Over 200 W of power output was achieved with this device made of similar banks of TE elements as used in phase 3.

The objective of phase 5 of this program was to improve on the phase 4 results and successfully design and build two TEGs and install and test them in both BMW and Ford vehicles. Another goal of phase 5 was to upgrade the models to the cylindrical construction. A complete description of the device-level modeling development can be found in Crane.[8] Initial phase 5 results along with the validation of the steady-state and transient models were extensively described in Crane et al.[9] Vehicle system-level modeling studies and results related to the program have also been previously described.[10,11]

FURTHER BENCH TEST RESULTS AND MODELING ANALYSES

In Crane et al.,[9] initial bench test results were reported for the first higher-temperature TEG produced. Bench tests continued on a second higher-temperature cylindrical TEG produced for the project. A sample of these test results is shown in Fig. 1. Despite the fact that this was a different TEG, the model was able to effectively predict performance for it as well. This second TEG produced a maximum power output on the test bench of 712 W. This improvement over the first higher-temperature TEG, which achieved a maximum power output of 608 W, is due to lower interfacial resistances.

ENGINE DYNAMOMETER TESTING

Following bench testing, the second TEG was sent to Environmental Testing Corporation (ETC), supervised by the National Renewable Energy Laboratory (NREL), for performance testing on an engine dynamometer. The test setup included a BMW six-cylinder engine and an exhaust component, including the catalytic converters. The TEG was mounted downstream of the catalytic converters and tested over a range of steady-state engine conditions at different coolant temperatures and flow rates. The TEG was also tested over the US06 drive cycle. Results from these tests are shown in Figs. 2 and 3.

Figure 2 shows steady-state test results for engine conditions that ranged from 1300 RPM to 3000 RPM and 50 Nm to 105 Nm. Coolant temperatures ranged from 30°C to 80°C, and coolant flow rates ranged from 10 lpm to 20 lpm. Expected trends can be seen from this data, as the TEG power output increased with engine RPM and torque. TEG power output was also higher at lower coolant temperatures and higher coolant flow rates.

Figure 3 shows the results of TEG performance during the US06 drive cycle. The US06 drive cycle is an aggressive drive cycle that is representative of highway driving with significant accelerations. The result of the more aggressive drive cycle is higher loads on the engine and more waste heat for the TEG to convert to electricity. Two cycles were run back to back with a 60-s idle in between. The cycles were run at coolant temperature of 80°C and 55°C to show what could be a possible benefit of using a lower-temperature, auxiliary radiator. There was an almost 50 W to 100 W improvement in power output for many conditions for coolant temperature of 55°C compared with 80°C. Figure 3 shows the power output for these tests with a maximum power of over 500 W achieved. It should be noted that the bypass valve control scheme could not be implemented for these tests. Thus, the bypass could only be either open or closed. Figure 3 also shows the TEG power output with a basic bypass valve strategy of fully open or fully closed. A throttling bypass valve would be expected to show performance in between the two curves.

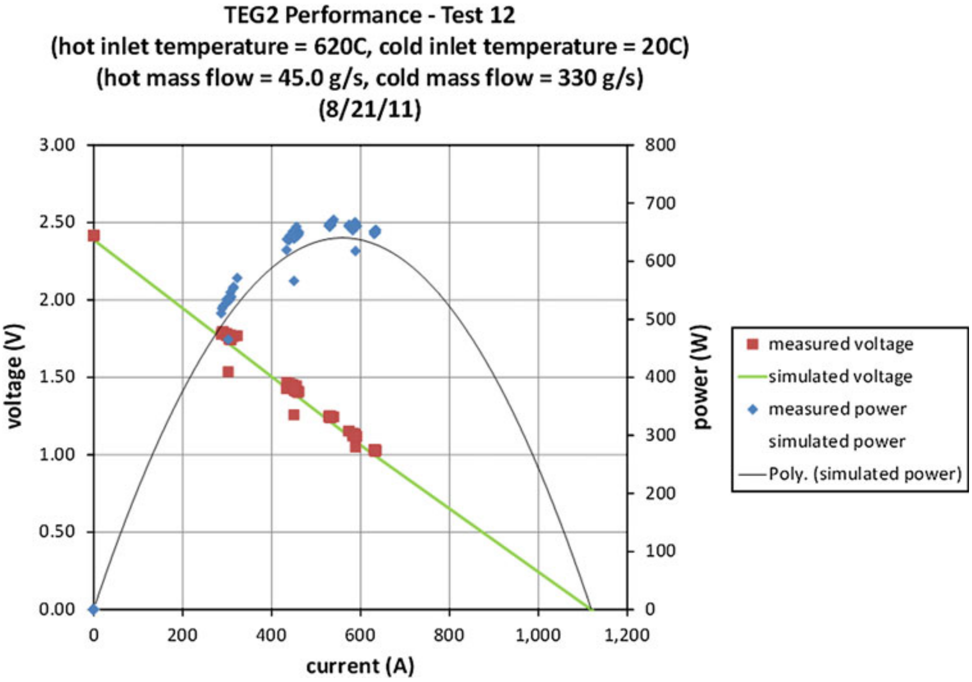

Fig. 1. TEG bench test results for the second higher-temperature cylindrical TEG compared with simulated test results for TEG voltage and power output.

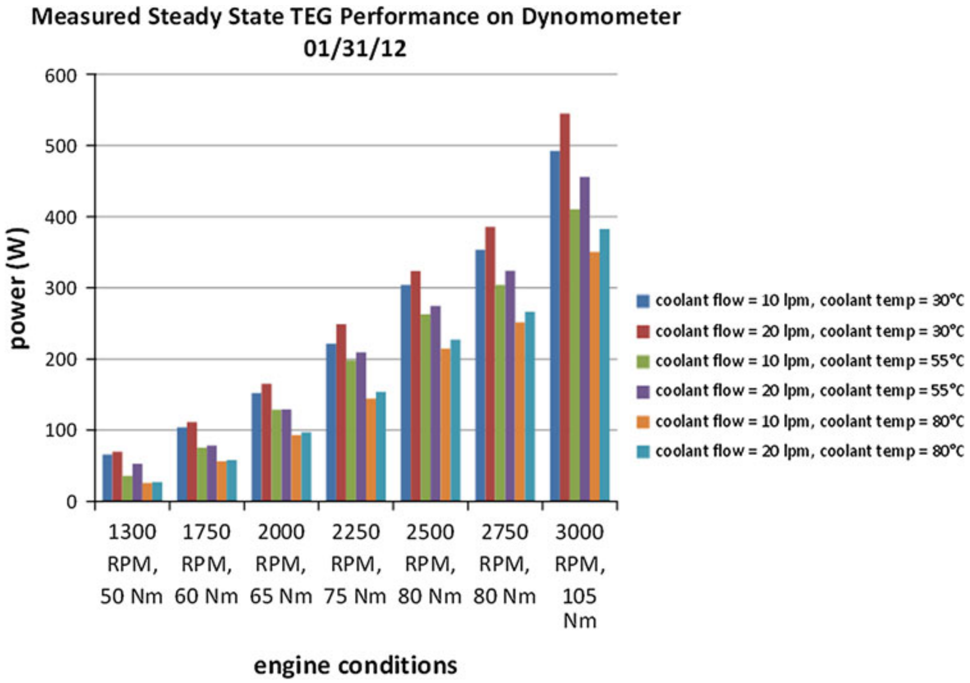

Fig. 2. Measured steady-state TEG performance on the engine dynamometer at various RPM, torque, and coolant temperature and flow.

BMW VEHICLE TESTING

One of the TEGs was integrated into a BMW X6 35i xDrive test vehicle for a final system evaluation in an application-oriented setup. The focus of the system integration was to minimize the negative impact on the regular vehicle components (for example, the cooling system, engine performance, etc.) whilst promoting optimal TEG performance.

The thermoelectric generator has a variety of interfaces and interactions with the surrounding vehicle. To analyze the impact of the TEG on the total system performance, numerous temperature, voltage,

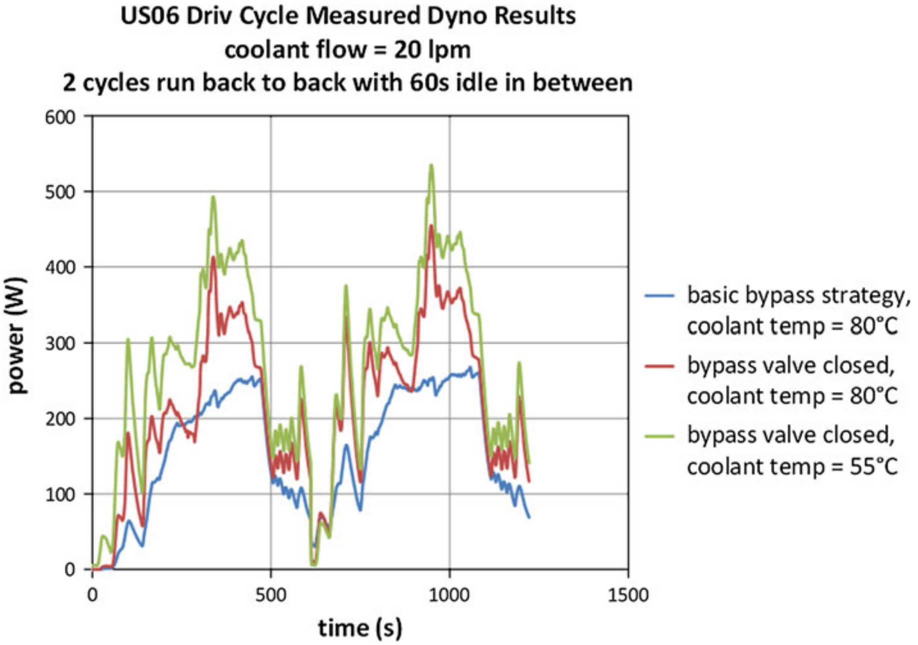

Fig. 3. TEG power output for TEG over the US06 drive cycle with bypass valve fully closed or with a basic bypass valve strategy.

electric current, differential pressure, and volume flow sensors were installed. An A/D signal converter merges all data channels into a digital CAN communication network. An application-specific engine control unit (ECU) provides additional information about engine-related values such as engine speed, load, and fuel consumption. Furthermore, an automotive control unit is installed to gather all measured data and ECU values and process them by means of a developed control strategy. In particular, the exhaust valve and the auxiliary water pump are controlled in a closed-loop circuit for optimal utilization of the TEG during dynamic and volatile driving conditions.

The electric power generated by the TEG strongly depends on the temperature level of the coolant, as shown in the dynamometer tests. Furthermore, BMW vehicles have a specific heat-up strategy to reduce fuel consumption and increase passenger comfort. The overall objective was to maintain the lowest coolant temperature for the TEG whilst keeping the engine unaffected by this additional component in the cooling loop. Hence, the TEG was installed in parallel to the engine with an auxiliary water pump to generate a sufficient coolant flow rate (Fig. 4).

The coolant temperatures are measured at the inlet and outlet port of the TEG in conjunction with the coolant volume flow rate. Based on these values, the demand value of the auxiliary water pump is controlled with the goal of minimizing the power consumption while ensuring sufficient cooling power. A nonreturn valve in the TEG tube prevents fatal damage of the engine in the event of auxiliary water pump failure.

The TEG component has a high number of parallel current paths and a limited amount of electrical serial TE elements. Therefore, the voltage level of the TEG is too low to use a DC/DC boost converter for direct integration into the vehicular power circuit, which has a typical voltage of 14 V. Hence, in this particular prototype vehicle the generated electrical power from the TEG is not utilized to lower the load on the alternator. Rather, a fixed electrical resistor is used to simulate the electrical load on the TEG and is equipped with voltage and temperature sensors for precise calculation of the generated power. The impact on fuel consumption is determined by a calculated shift in the engine map based on the TEG power divided by the actual alternator efficiency.

The TEG is installed upstream of the middle muffler, roughly 1 m behind the main catalyst. To maintain the exhaust gas temperature as high as possible at the TEG inlet, the exhaust line between the catalyst and the TEG is encapsulated by a thermal insulator (Fig. 5).

A critical role is assigned to the exhaust valve at the rear end of the TEG. The valve can be opened continuously and splits the total exhaust stream between the outer TEG section and the internal bypass path. This distribution of exhaust between the two paths has a high impact on the exhaust backpressure, the heat rejected to the cooling system, and the temperature of the TE elements. The goal of the closed-loop exhaust valve control strategy is to maintain the highest possible power output by the TEG whilst keeping the previously mentioned system values below the allowed limits. This three-level strategy is displayed in Fig. 6.

The first level determines the optimal exhaust valve position with respect to the system temperature.

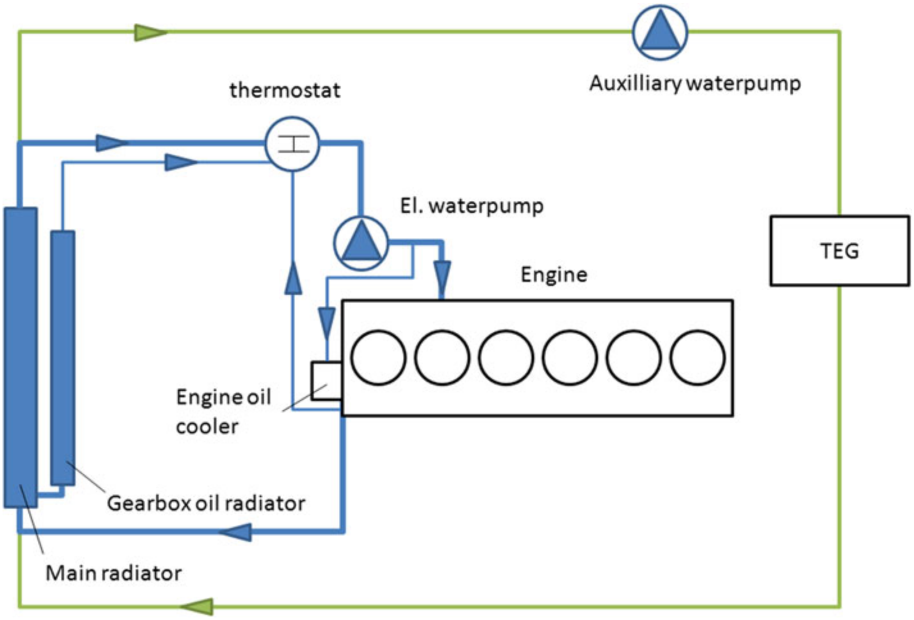

Fig. 4. Integration of the TEG into the cooling system of the prototype vehicle.

Fig. 5. TEG integration into the exhaust line of the BMW X6 prototype vehicle.

This value is passed on and further limited by the second level, which takes the engine load and engine speed into consideration. The third and last level requests a fully opened exhaust valve in case of a detected emergency (e.g., temperature limit, pump failure, etc.).

The exhaust temperature as well as the exhaust mass flow rate increase with increased load on the engine. Hence, the exhaust enthalpy is strongly dependent on the vehicle speed. However, the utilized exhaust stream has to be restricted at higher speeds due to two primary aspects:

- The temperature limits of the thermoelectric material;
- The exhaust backpressure of the TEG results in negative effects on the combustion process.

In summary, this leads to a peak in the electric power for the so-called design point, which was chosen for this specific prototype vehicle at 125 kph (78 mph). Additionally, the highest power output is reached for constant driving conditions due to the thermal inertia of the TEG component. Figure 7 shows the measured power output and the calculated fuel consumption reduction for various vehicle speeds.

The prototype vehicle was tested on a closed track. Each data point represents the final value after several minutes of driving at constant speed. It is evident that the power output increases with speed due to the rising exhaust enthalpy. At the design point, a TEG power output of 605 W was measured. The relative change in fuel efficiency improvement depends on the actual fuel consumption, which increases with increasing vehicle speed. Therefore, the two curves in Fig. 7 have different slopes and the relative improvement in fuel efficiency culminates at ~110 kph at a value of over 1.2%.

The closed-loop control strategy of the TEG system enables an unaffected driving behavior of the prototype vehicle compared with a regular car. An installed data-logger saves the measured and calculated values during usual and dynamic test drives. Figure 8 shows a representative use case.

Similar system behavior is observed for constant and dynamic driving conditions, as the power output rises with increasing speed. A limiting factor is the need to open the exhaust valve during the acceleration phases (hence a loss of exhaust enthalpy for the heat recovery system) in addition to the thermal inertia of the component.

Therefore, the achieved power output is ~450 W for a vehicle speed near the design point, in contrast to more than 600 W for similar steady-state conditions. Repeated test drives showed no degradation in power output of the component for the first few months. Further tests will be conducted as a

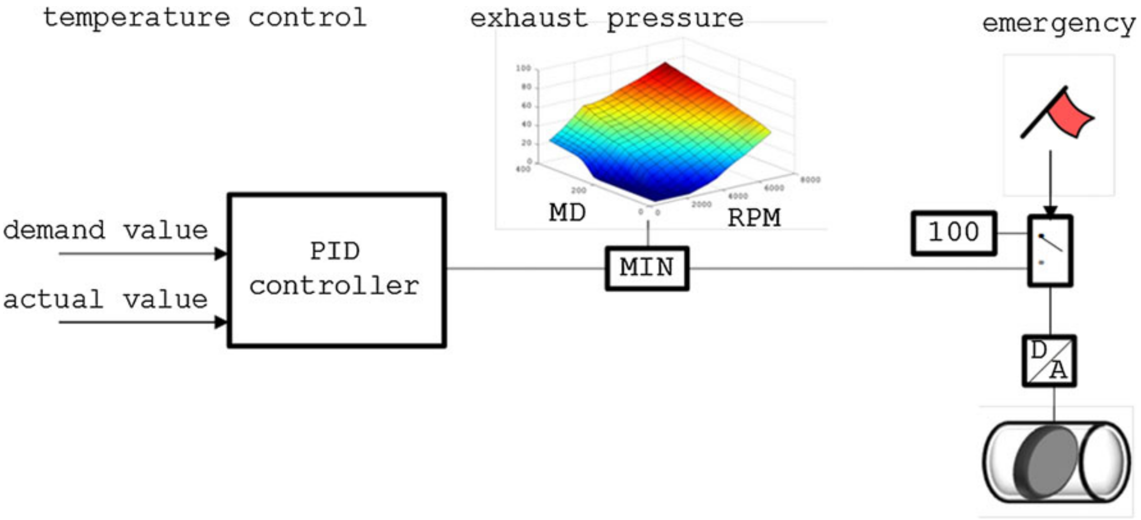

Fig. 6. Three-level control strategy of the exhaust valve.

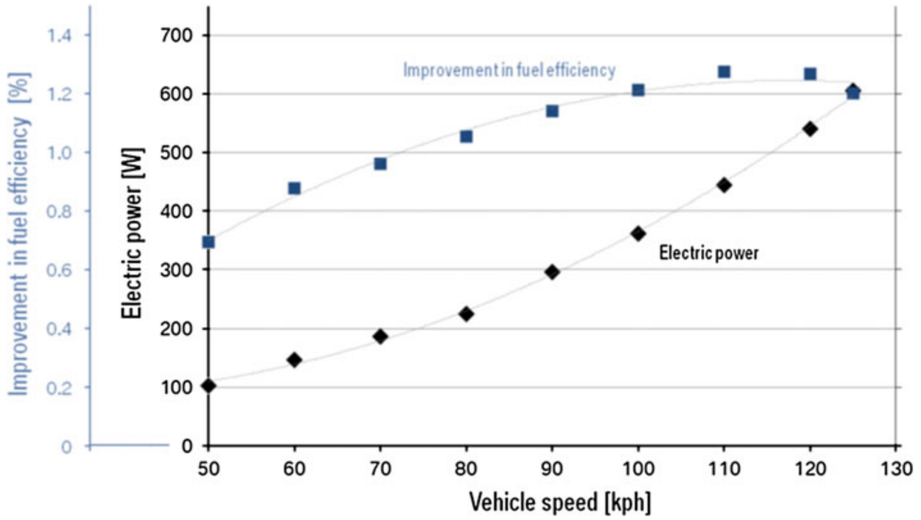

Fig. 7. Power output of the TEG and the improvement in fuel efficiency over vehicle speed.

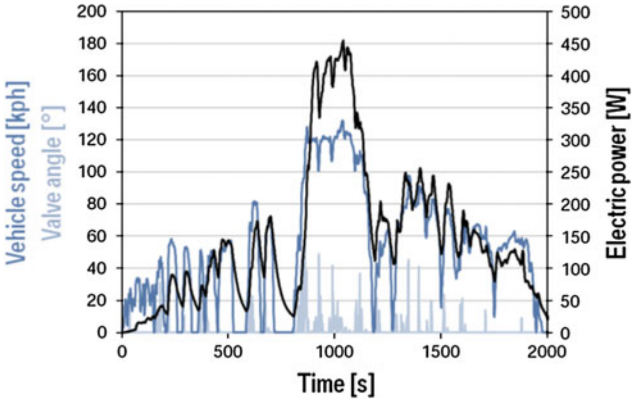

Fig. 8. Electric power output, vehicle speed, and exhaust valve angle over time for a dynamic test drive.

first indication of the thermomechanical durability of this component.

FORD VEHICLE TESTING

A phase 5 TEG was integrated into a Ford Motor Company vehicle for on-road testing as well. The vehicle selected for the integration was an all-wheel-drive 2011 Lincoln MKT with a 3.5-L V-6 twin-turbocharged gasoline direct-injection engine and a six-speed automatic transmission. This vehicle has rated fuel economy of 16 mpg city and 22 mpg highway, and the engine is rated at 355 horsepower at 5700 RPM and provides 350 lb-ft of torque at 1500 RPM to 2500 RPM.

To minimize interference with or degradation of vehicle emissions, the TEG was mounted downstream

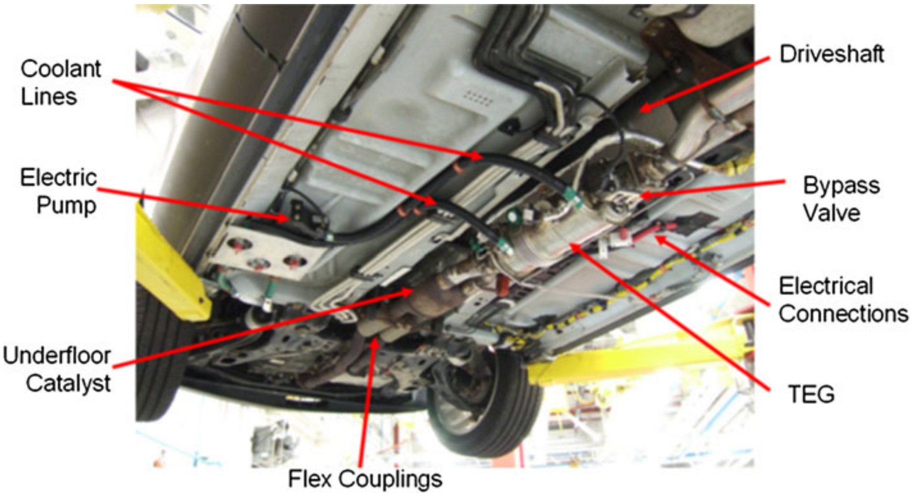

Fig. 9. Integration of the TEG into the underfloor of the test vehicle. The front end of the vehicle is at the bottom left of the image.

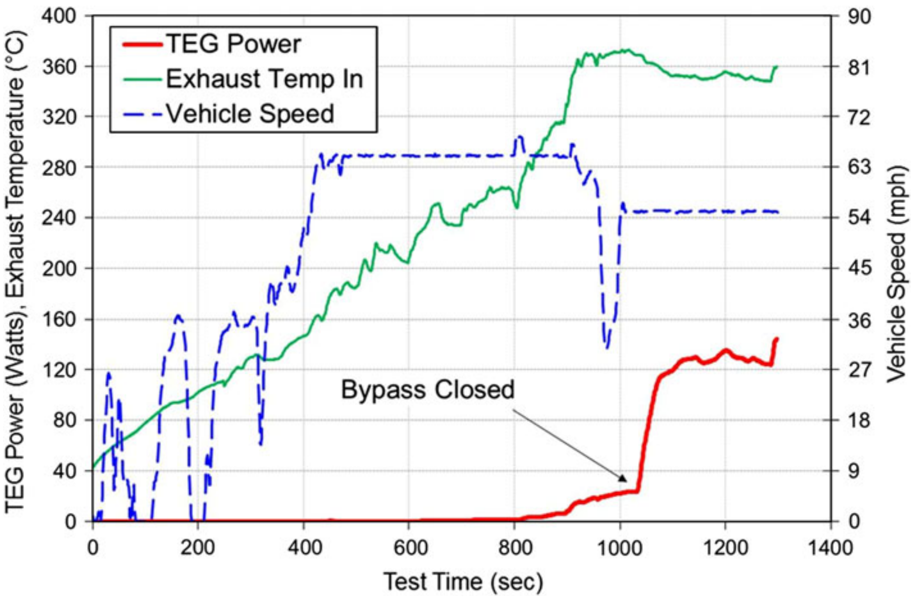

Fig. 10. Test data showing TEG cold-start performance; the bypass valve was closed once the vehicle entered the 55 mph steady cruise portion of the test.

of the light-off and mid-body catalysts. This placed the inlet to the device nearly 2 m from the outlet of the exhaust flanges. The cooling circuit was integrated directly into the vehicle primary cooling system. Similar to the BMW installation, electrical power generated by the TEG was dissipated in a matched load resistor. The mounting and integration of the unit is shown in Fig. 9.

The testing consisted of over 50 h of on-road evaluations at various operating parameters. These included cold-start, highway steady-speed cruise, and city stop-and-go driving. An example of each type of drive event is shown in Figs. 10–12 to provide results typical of the performance measured during the total test evaluation phase.

At the conclusion of the tests in the Ford vehicle, the TEG was removed and tested again on the test bench. An example from these new bench tests is shown in Fig. 13. It can be seen that no degradation took place between the tests conducted on 8/22/11, before the TEG was installed on the Ford vehicle, and 7/23/12, after the TEG was tested on the Ford vehicle. This shows the robustness of the TEG through the performance (both voltage and power) repeatability of the bench tests.

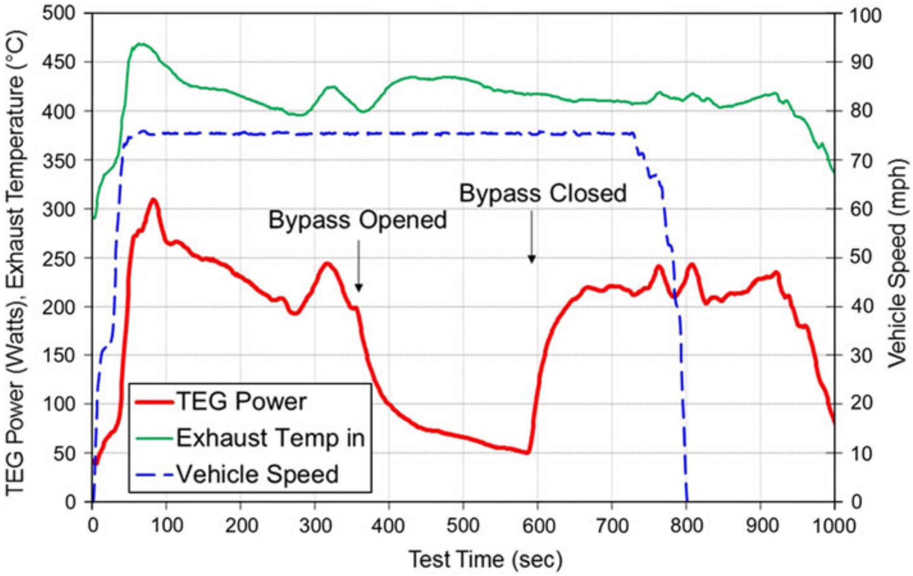

Fig. 11. Test data showing typical TEG highway cruise performance at 75 mph; with the exhaust bypass valve closed, the TEG generated roughly 225 W of power.

TECHNICAL STATUS AND BARRIERS

At the conclusion of the project, there are still many technical issues to address to help make the TEG more commercially ready. On the TE material side, there is always the desire to improve the average *ZT* of the material for the desired temperature range. This will improve the efficiency of the TEG and thus expand its potential. That said, the current TE materials that are available offer sufficient average *ZT* to enter the market.

Other aspects of the TE material may be more critical at this time, including mechanical robustness and sublimation and oxidation suppression. Without further development in these areas, the TEG may not be able to reach the desired operating lifetime.

Further development is also needed on TE material metallization and contact resistance. In developing TEG engines, it is critical to manage the coefficient of thermal expansion (CTE) mismatch between TE material and its connectors as well as the thermal expansion between the hot and cold sides of the device. This is not an easy task while still maintaining contact/interfacial resistances as low as possible. This is made more challenging by the need for electrical isolation between the heat exchangers and the TE elements.

The key technical issues that currently limit performance at the TE engine level include heat loss between the hot and cold sides as well as to the environment and the low heat transfer rates possible with gas convection.

TEG issues include minimizing the gas-side pressure drop while still maximizing the gas-side heat transfer. Weight also is an issue, particularly relating to transient operation and warm-up time.

System integration issues include weight, volume, engine backpressure, voltage, noise, and catalyst light-off.

ECONOMIC VALUE STATUS AND BARRIERS

Over the five phases of the program, the team worked to evolve a TEG system architecture that provided a balance of cost and performance. In the initial phase of the program, a secondary loop system was proposed that provided several benefits:

- Reduced TEG volume, which helped address hermetic packaging and recycling concerns
- A means of buffering the dynamic nature of exhaust gas enthalpy as a function of typical driving conditions in the city
- Providing a closed-loop hot fluid to reduce TEG heat exchanger fouling

Although the proposed architecture provided significant technological benefit, the requirement for the secondary loop pump and working fluid drove the system cost to an unacceptable high level.

In the third phase, an inline TEG system was proposed, comprising alternating hot (exhaust gas) and cold-liquid flat heat exchangers, between which thermoelectric engines were “sandwiched.” This architecture reduced the overall system cost but it was found that the manufacture of the flat plates required extraordinary process control (flatness, parallelism, and smoothness) that again drove manufacturing costs higher than desired.

As a result, a cylindrical TEG architecture was developed in phase 4, which not only had the benefit of simplifying the TEG construction but also provided a volume reduction for the system by internalizing the exhaust gas bypass within the TEG.

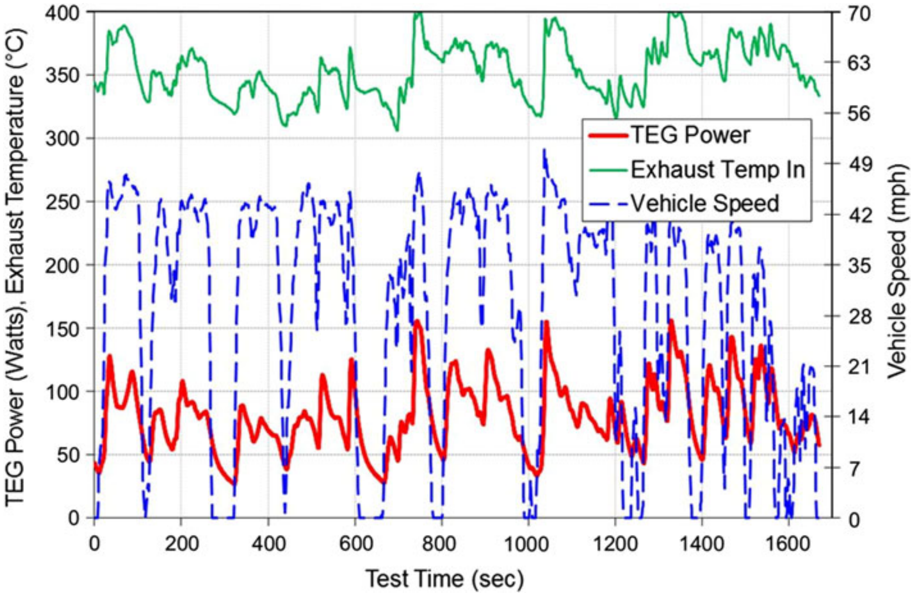

Fig. 12. Test data showing typical TEG city driving performance; with the exhaust bypass valve closed, the TEG generated roughly 80 W of power on average.

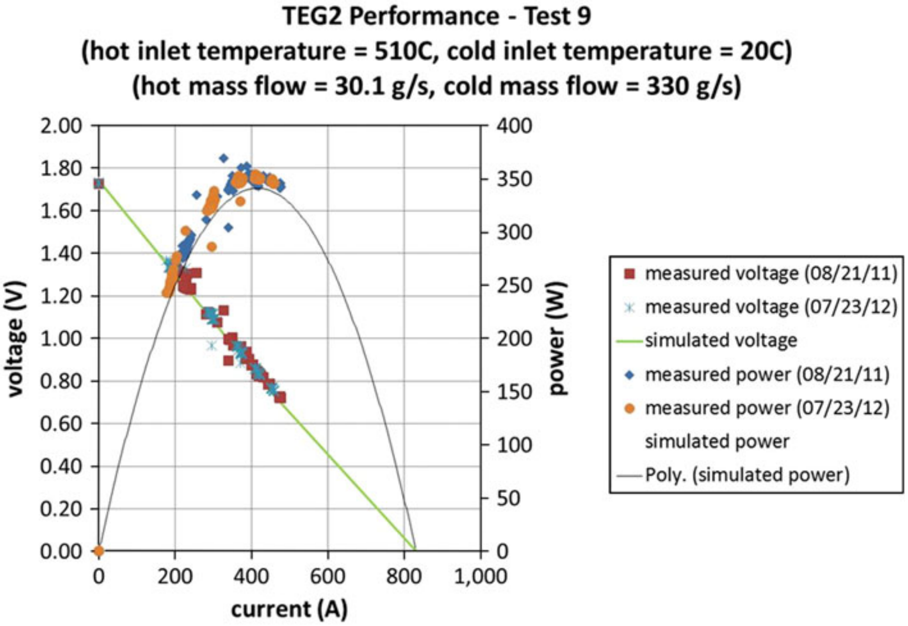

Fig. 13. Repeatability of TEG bench test results from before on-vehicle testing to after on-vehicle testing for TEG voltage and power output.

This design was built and tested in vehicles in phase 5, confirming the stack engine design and cylindrical architecture as a go-forward design concept.

In parallel with the evolution of the TEG and vehicle system architectures, TE material systems were evaluated for economic viability. In the course of internal analysis it was concluded that tellurium-based materials would be cost-prohibitive for this application, which assumes mass automotive deployment of TEG and uses bulk TE materials. Alternative material systems are being evaluated based on the combination of criteria including thermoelectric performance, technology readiness level, and projected cost of mass production. No material satisfies all the requirements today, and no material is mass-produced beyond bismuth telluride and lead telluride; however, the challenges towards commercialization are different for different material systems. Taken together, these criteria resulted in a decision to focus on cobalt antimonides [skutterudites (SKD)] for the next phase of work.

At the time of publication, SKD materials and ohmic contact systems are at an appropriate maturity level technically to support their further development. These materials, as well as other thermoelectric power generation materials that operate with hot-side temperature in the range of 500°C, are not available commercially. While they can be made using industry-standard powder metallurgy processes, the necessary manufacturing infrastructures are not in place to support commercialization of automotive TE heat-to-power conversion. Additional work at the TE material level involves reducing the amount of high-purity material needed as well as the number of processing/manufacturing steps. On the TE engine and TEG side, there is a need to further reduce the total number of parts and to reduce the number of parts that require high tolerances. At the system level, more work is needed to develop an appropriate power conversion scheme, including power-point tracking and DC/DC conversion. This work is a necessary precursor to implementation of the technology and must be addressed. For the TEG cost to meet market requirements, it is estimated that the TE elements would need to be produced and metalized at a fraction of today's cost, or roughly a few US cents per die.

NEXT DOE PROGRAM AND IMPACT OF RELEVANT NONAUTOMOTIVE WORK

A new DOE-sponsored program has begun (DOE award #DE-EE0005387). This program will address many of the issues described above. The target for this new program is to develop a TEG that will provide a 5% improvement in fuel economy over the US06 drive cycle while still being on a commercialization path for 100,000 units/year. This is a challenging goal, and one that the team is already attacking.

In addition to passenger vehicle development work, there is also the potential for TEG development work for other applications, such as industrial waste heat recovery, trucks, aerospace, and primary power generation. These types of programs, whether commercial or government funded, can significantly aid TEG development, particularly if the TEG architectures can be kept synergistic with the passenger vehicle solution. These types of programs may play a fundamental role in the commercialization part of the equation.

CONCLUSIONS

Two TEGs have been successfully integrated and tested on a BMW X6 and Lincoln MKT with over 600 W of power produced in vehicle tests and over 700 W produced in bench tests. Models have been created that can successfully capture TEG performance in both steady-state and transient conditions. These models have been integrated into vehicle system-level models as well. With the validation of the models against experimental data, the simulation tools can be used to optimize the geometries and operating schemes of TEG designs. The technical and economic barriers have been identified. Challenges most certainly still exist. One DOE program has ended, and a new DOE program has begun that will allow further development of TEG technology for passenger vehicle waste heat recovery.

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